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A BASE-ISOLATED SYSTEM FOR SEVERE ACCIDENT-MANAGEMENT AT BEZNAU NPP

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ABSTRACT

An effective countermeasure for Severe Accident-Management (SAM), consisting of an additional base-isolated Diesel Generator System was built at Beznau NPP in June, 2013. Aim of this paper is to describe scope, design-basis as well as technical aspects related with the adopted base-isolation system. The decisional process for the choice of the appropriate base-isolation system will be presented. Further, aspects of seismic robustness will be addressed and discussed. Finally, a cost-to-safety effectiveness of this measure with respect of Core Damage Frequency (CDF) will be shown with the aim to provide some decision making basis for similar projects at other NPP sites.

INTRODUCTION

After the destroying Tohoku Earthquake (Mw=9.0) of March 11th, 2011 off Japans' East Coast and the subsequent tsunami event, a major nuclear accident occurred at Fukushima Daiichi NPP. In accordance to current practice and standards in the nuclear industry, the Swiss Nuclear Safety Inspectorate (ENSI) ordered an extensive review and proof of the five existing Swiss NPP Units against external hazards such as earthquake and flooding. Although ENSI confirmed, that all five existing NPP Units accomplished the required safety criteria by July, 2012 several additional SAM-measures were prepared.

BEZNAU NUCLEAR POWER PLANT

General Information

The Beznau nuclear power plant is one of the four existing Swiss NPP stations. It is located in the municipality of Döttingen (Canton of Aargau) on an artificial island in the Aare river (Figure 1). Beznau NPP consists of two identical PWR units with an electrical power of 365 MW delivered by Westinghouse Electric. On December 24, 1969 Beznau Unit 1 started commercial operation, followed roughly two year later by Unit 2.

Although four and more decades of reliable energy production, Beznau NPP has continuously been upgraded to meet modern nuclear safety standard requirements as well as state-of-the-art technology. Among other, the following refurbishment and upgrading projects have to be mentioned:

- New bunkered and very robust emergency buildings
- Replacement of the steam generators
- Replacement of the refuelling water storage tank
- New separate diesel generator buildings

Moreover, periodical safety studies (i.e. seismic PSA) provided insights on the plants reliability since the late 1980ies. Hence, potential refurbishment or upgrading studies were always evaluated on a common objective and coherent basis by comparing invested monetary amount with respect of risk reduction (i.e. Core Damage Frequency and Large Early Release of Radioactivity).

Figure 1. Aerial view of the Beznau NPP Twin-Unit Site (left) and location of location of the new diesel generator system for SAM on top of the bunkered emergency building (right)

Defence in Depth in Nuclear Safety

According to national and international nuclear safety provisions, defence in depth at Beznau NPP is provided by at least four safety stages acting at different Plant state conditions (see Table 1). Governing of an accident within design basis conditions corresponds to the safety stage 3. By an extreme accident beyond design basis conditions, several countermeasures and specific severe accident management guidelines (SAMG) will prevent a potential core damage or mitigate its consequences (stage 4a-b).

Table 1: Defence in Depth Nuclear Safety Stages Definition

Stage	Goal(s)	Instruments	Core State
1	prevention of abnormal plant conditions and errors	conservative design basis and high quality during of execution	prevention of core damage
2	abnormal plant conditions management and detection of errors	regulation and protection systems, periodical tests and inspections	
3	accident plant conditions management within design basis	safety systems, accident and emergency guidelines	
4a	extreme accident plant conditions management prior to core damage	fix installed and mobile equipment, SAMG for core damage prevention	
4b	extreme accident plant conditions management after to core damage	fix installed and mobile equipment, SAMG for core damage mitigation	mitigation of core damage
5	mitigation of the radiological consequences	external emergency response	

By definition, each plant design is defined by (a) a wide range of possible accidents and (b) specific safety and emergency systems that have to fulfil integrity and functionality requirements within design basis conditions. On the other hand, a beyond design basis (BDB) accident occurs if at least one of the two requirements (a) or (b) has become invalid.
In the wide majority of the cases, a BDB accident does not lead directly to core damage, because of redundancy, automation, room separation, qualification or inherent safety margin of the relevant

Structures, Systems and Components (SSC). Nonetheless, past experience has shown the importance of fixed installed and mobile SAM equipment on the light of preventing and/or mitigating core damage.

IMPACT OF THE FUKUSHIMA DAIICHI ACCIDENT ON ACCIDENT MANAGEMENT

Reitnau Storage for Severe Accident-Management

The nuclear accident at Fukushima Daiichi NPP pointed out, beside the importance and the need of an adequate severe-accident preparedness, that NPPs must have quick access to additional equipment such as pumps, emergency generators, tubing or fuel. As a consequence, ENSI ordered the Swiss NPP operators to set up a common external store for this emergency equipment. The external storage was established at a former munitions storage of the Swiss Army at Reitnau in Aargau. It started operating on June 1, 2011 less than three months after the Tohoku Earthquake had occurred.

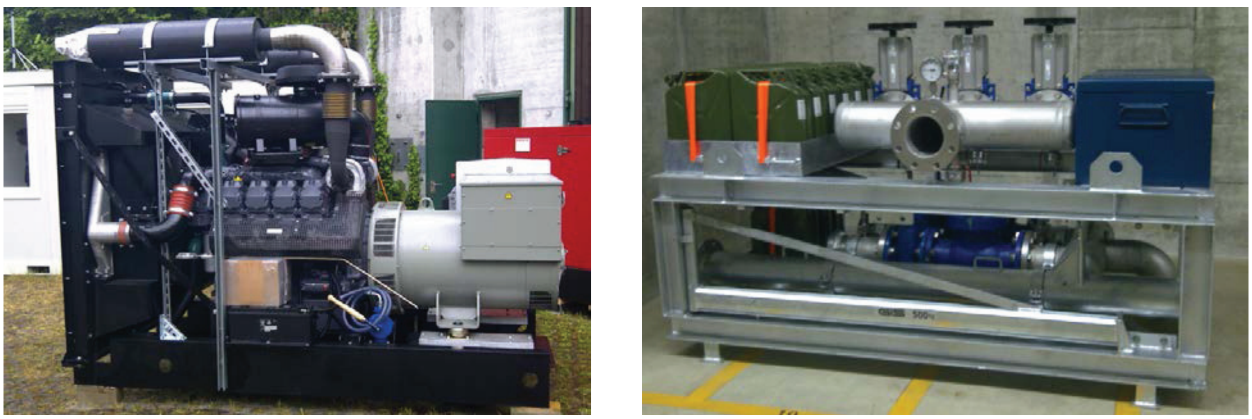


Figure 2. Aggregate for the production of energy (left) and equipment for the fire-brigades (right) stored at the former Swiss Army storage at Reitnau in Aargau

In consideration of the possible destroying force of extreme earthquake events on infrastructure, ENSI explicitly required that the equipment at Reitnau storage is transportable by air. For this task, a Swiss Army Super Puma helicopter would provide the NPP operators the adequate assistance. Figure 2 shows as example equipment stored in Reitnau.

Accident-Management Diesel Generator (AM-DG) Unit at Beznau NPP

In addition to the regulatory provisions after the Fukushima Daiichi NPP accident, an extensively critical review process was undertaken by the NPP Operators. Aim of the project was to detect possible cost-effective improvements at SAM level and to get them implemented. Among others, a very efficient countermeasure was identified in the constitution of a base-isolated platform for the storage of a diesel generator aggregate and equipment. Based on criteria such as reliability, robustness and operational, it was decided to place this additional energy supply equipment on the top of the emergency building.

NEW ACCIDENT MANAGEMENT DIESEL GENERATOR SYSTEM

Conceptual Design Issues

Based on the primary scope of the new diesel generator, it was conceptually decided to place the additional AM-DG on base-isolated structure. In fact, this would guarantee a high response reliability, a great energy dissipation and therefore ensure a system’s functionality even for severe ground shaking beyond Safe-Shutdown Earthquake (SSE) level. Also due to the considerable height of 17 m of the emergency building's roof above ground, a very effective protection against flooding or heavy rainfall is ensured.

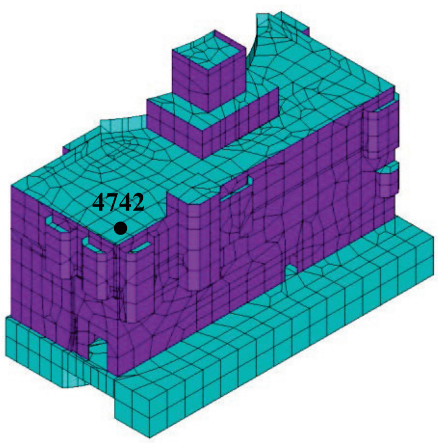
Interdisciplinary Consideration

Interdisciplinary considerations as requirements of NPP operators were already addressed at an early stage with the aim of providing (a) a technical feasible solution (b) a time-efficient operation in case of an accident (c) a widely acceptance of the new SAM system. Despite this may appear to be somewhat obvious past plant experience indicates, that especially for (non-generic) SAM only well reasoned solutions may be efficient due to (a) lack of time or (b) lack of human resources for their applicability.

DESIGN PROCESS OF THE BASE ISOLATION SYSTEM

Seismic Hazard Definition and Design Goals

The design of the new AM-DG structure is intended to resist very high seismic event loadings, even significantly larger than the actual 10^{-4}/a design review level (arising from SSHAC level 4 PSHA PEGASOS Refinement Project). Due to this fact, that the design strategy adopted consists of a structural solution effective at the normal design but also at more severe design conditions (hazard scaling factor *f>1.0*). Moreover, the new reinforced concrete structure was designed relying on capacity design principles: columns and base isolated slab were therefore designed to resist seismic forces larger than the maximum seismic force which could be transmitted by isolators at rupture. In other words this means, that isolator failure could be identified as the key parameter for structural robustness of the new AM-DG.



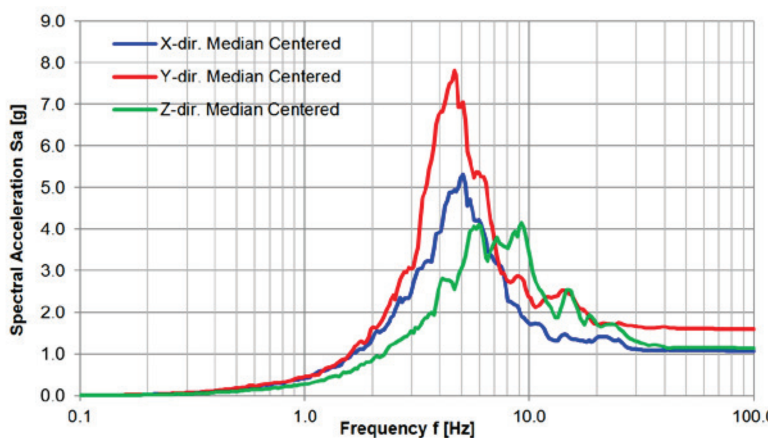


Figure 3. SASSI-Model of NANO-building (left) an TH-Response Spectra for PRP-IMH UHS with 1g PGA normalized input and 5% critical damping for structural node 4742 (right)

Seismic Isolation Devices Review

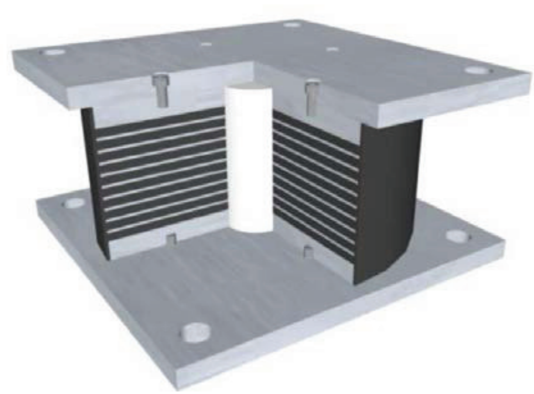
Based on the specific characteristics and goals of the project, as (a) low mass of the design system, (b) beyond design reliability and (c) force-transmittal control into the primary emergency building structure, a feasibility study was carried out. Among others, the following isolator systems were considered: friction pendulum system (FPS), high and low damping rubber bearing (HDRB, LDRB) and Lead Rubber Bearing (LRB). After the feasibility evaluation, LRB isolator devices were chosen for the subsequent project stages. Advantages and disadvantages of the considered isolator systems can be seen on Table 2.

Table 2: Characteristics and feasibility conclusions of each isolator system

System	Main properties	Feasibility conclusions
FPS	- frequency theoretically depends only on the bearing radius (mass independent) - friction forces at sliding interface, however, must be overcome before sliding occurs - static friction coefficient is expected to vary significantly form theoretical values	- theoretically best option due to low mass of design system mass, however - usually designed for significantly higher axial loads, therefore - potential, that system will work as an horizontal fixed link, has to be considered
HDRB, LDRB	- isolator works linear elastic with very low stiffness and variable damping ratio - due to the high flexibility, rupture will occur at maximum lateral displacement (allowable rubber strain or bearing instability)	- linear elastic behaviour will not limit force increase until device rupture will occur - effectiveness only for low stiffness values - isolator is susceptible to heat related property changes during cyclic loading - isolator is susceptible to aging related property changes during time
LRB	- isolator works as an elasto-plastic systems with initial and post-yield stiffness - due to the core lead contribution, high hysteretic damping will be provided (see Figure 4)	- elasto-plastic behaviour and appropriate chose of yielding force ensure force-control - reliable systems response even for beyond design level is expected

Description of the Lead-Rubber Bearing Isolation System

The base isolation system consists of four LRB isolator devices positioned on each corner of the reinforced concrete plate with dimensions of B x L = 6.5 m x 7.5 m and slab thickness of t = 0.3 m. Massive reinforced concrete columns below each device support transmits shear and axial loads of the superstructure into the emergency building. The existing roof of the emergency building (see Figure 3) consists of a 1 m thick reinforced concrete plate and is therefore able to sustain the additional loads of the new system without difficulty.



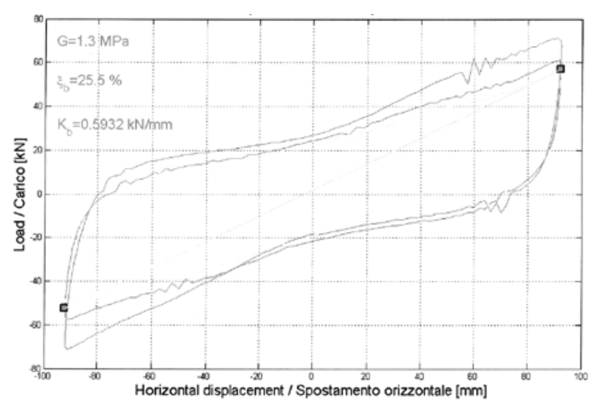


Figure 4. Layered construction of a LRB with lead core (left) and typical hysteretic behaviour with high energy dissipation loops (right)

Design and Verification Process

Starting from a SASSI model of the emergency building with median centred properties a deterministic SSI-analysis with PRP Intermediate Hazard (PRP-IMH, 10^{-4}/a soil surface, mean UHS) was carried out for the purpose. Further, nodal time history seed corresponding to the AM-DG location on the emergency building's roof (see Figure 3) was used as input for the design of the base isolation system model (SeismoStruct). In order to carry out a robust design of seismic isolated structure, two hazard conditions were considered at design basis level having scaling factors *f=1.0* and *2.0* of PRP-IMH.
As already mentioned before, capacity principles were adopted for the design of all new reinforced concrete elements. Moreover, based on data of experimental tests on two LRB devices, the basic design assumption such as stiffness properties, yielding force and displacement capacity were checked, leading to following conclusions: (a) initial and post-yield stiffness assumptions are in good agreement with experimental tests (b) energy dissipation and displacement capacity assumptions are conservative with respect of experimental tests (c) difference lies in the expected engineering range.
On the light of periodic safety studies or aging management process all important project information has been documented and archived in the NPP document management system.

CONSTRUCTION PROCESS AND SYSTEM INTEGRATION

Construction Stages

A time and cost efficient solution took place by progressing in parallel for the execution of the capacity protected structure on top of the emergency building (columns and isolator devices) as well as at ground level (new reinforced concrete plate). Due to this reason, a mobile crane was required for the lifting of the 36 t heavy reinforced concrete on top of the four LRB isolator devices at emergency building's roof (see Figure 5). At this execution stage few centimetres of tolerance for the location of the sixteen isolator anchor bolts were considered.

Figure 5. Sequences of the reinforced concrete plate assembling on top of the isolator devices at roof elevation of emergency building

In the next construction step the containers with AM-DG and equipment were fixed on the reinforced concrete plate (Figure 6). Further, electrical cable trays as well as anchors for the diesel fuel supply were predisposed in order to ensure an high operational preparedness of the accident management system.

Figure 6. Final disposition of diesel generator and equipment (left) and container's fixation detail (right)

Implementation and Integration in the Plant Operational Specifications

A total of eight specific provisions were set up by the nuclear safety department in order to provide applicability guidance of the new countermeasures at safety stage 4. Moreover, existing emergency teams were introduced, instructed and trained to handle the new AM-DG system.

SEISMIC SAFETY ASSESSMENT OF THE BASE-ISOLATED SYSTEM

Probabilistic Soil-Structure-Interaction Analysis and Incremental Dynamic Analyses

In the framework of seismic PSA a probabilistic soil-structure-interaction analysis of the emergency building with SASSI was performed. For this scope, a seed of totally thirties, tree-component time-histories were generated and convolved with thirty SASSI analysis models. Soil and structure variability were properly considered in the analyses by scaling stiffness and damping values with Latin hypercube sampling methodology. Probabilistic SASSI results were evaluated at nodal level in terms of relative displacements, absolute accelerations as well as in-structure response spectra (ISRS) for 50% and 84% non-exceedance probability (see Figure 7). A composite variability equal to β_C=0.24 resulted for frequency range of the base isolation structure.

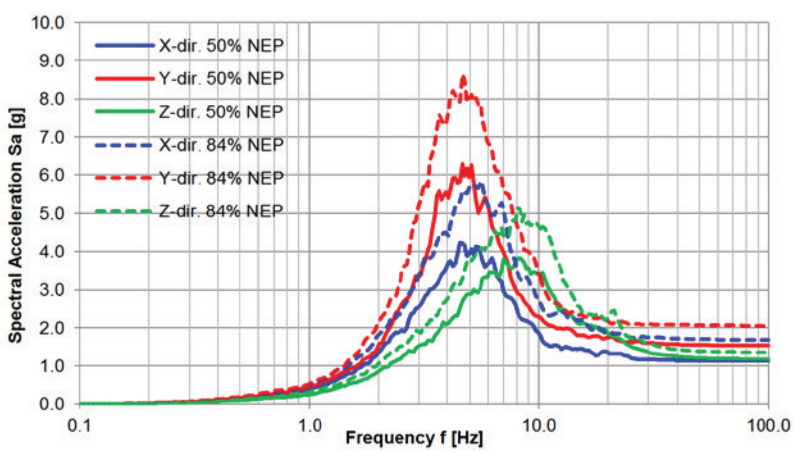


Figure 7. emergency building, three component probabilistic ISRS, 5% damping at roof level (El. 343.5) for PRP-IMH UHS with 1g PGA normalized input

Further, incremental dynamic analyses were run with identical FE-Model and time-history seed of the deterministic design. Following system peak response values were evaluated for each isolator: horizontal displacement, base shear-force and axial-load (see Figures 8 to 9). A comparison of the maximal response values with their capacity for a hazard scaling factor up to *f=4.0* of PRP-IMH shows, that: (a) displacement capacity (Δ_{Rd}=140 mm) as well as shear-force capacity (V_{Rd}=80 kN) are by far not critical while (b) load bearing capacity in combination with lateral displacement is approaching the ultimate limit state. At a lateral displacement of Δ_{Ed}=60 mm a load bearing capacity equal to N_{Rd}=350 kN can be sustained while at Δ_{Ed}=80 mm a roughly 20% lower axial capacity is guaranteed.

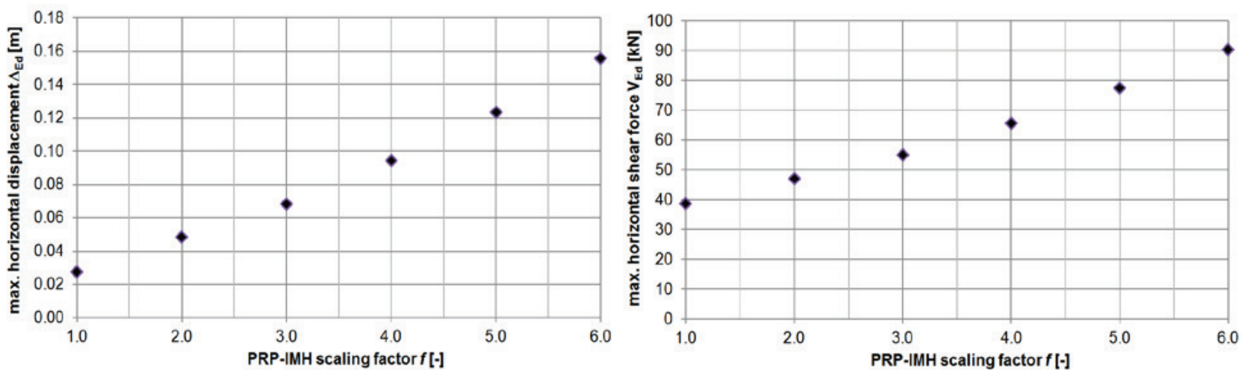


Figure 8. comparison of peak horizontal displacement (left) and shear-force (right) demand for the envelope of the four isolators as a function of PRP-IMH Level scaling factor *f=1.0 to 6.0*

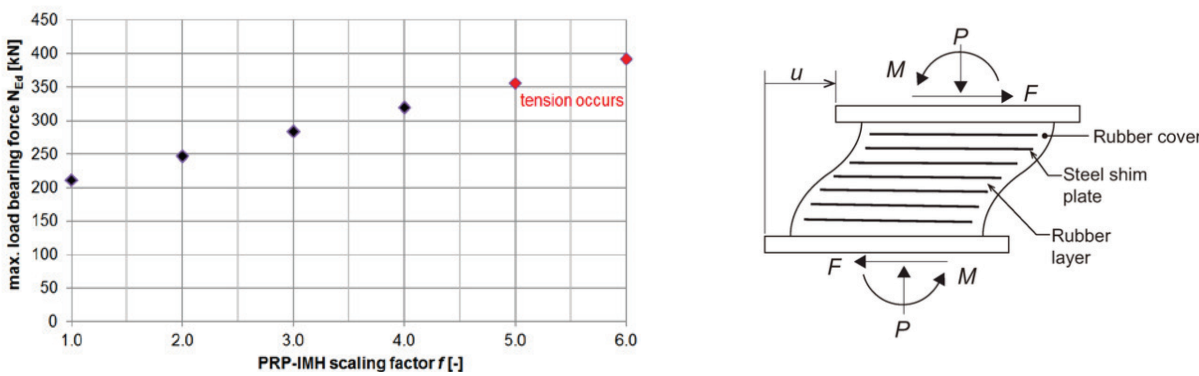


Figure 9. comparison of peak axial load demand for the envelope of the four isolators as a function of PRP-IMH Level scaling factor *f=1.0 to 6.0* (left) and isolator in the deformed configuration (right)

In observance of the fact, that peak axial load and maximum lateral displacement during seismic events statistically do not occur simultaneously was conservatively estimated, that local failure of the base-isolated system will roughly occur at an hazard level equal to four-and-half times PRP-IMH 10^{-4}/a exceedance probability. By scaling seismic demand (ISRS for 50% NEP) a median seismic capacity A_m=1.58 g was calculated. Finally, by considering appropriate aleatory uncertainty and epistemic variability on the capacity side, as well as results of isolator testing an high-confidence-low-probability of failure value (HCLPF) equal to 0.82 g was obtained.

Risk Reduction Evaluation of the New AM Diesel Generator and Investment Effectiveness

Beznau NPP has a strong history in PSA, both in Level 1 and in Level 2 and for full-power and for shutdown conditions. The current full-power PSA model includes nearly 2000 components, over 7000

Basic Events, over 300 Top Events and over 200 initiators. The common PSA software RISKMAN is used. For this investigation of the effectiveness the full-power model was used.

Starting from the existing PSA model the relative contribution of the new AM-DG was estimated based on the Risk Achievement Worth (RAW) and the Fussel Vessely Importance measure (FV). Whereas the RAW considers the importance of the component in terms of the change of the CDF, when the component fails with 100 %, the FV considers the importance on the CDF, when the component is 100 % reliable.

Due to the complex configuration of Beznau NPP including both, modern systems on different levels and original systems, the investigation did not only consider the current model as "base case", but also sensitivity cases to allow the application of results to other nuclear power plants. Therefore the following cases were investigated in terms of importance of the AM-DG:

(a) Current configuration of the NPP Beznau (base case)
(b) Configuration of the NPP Beznau without the separate diesel generator buildings
(c) Configuration of the NPP Beznau without the bunkered emergency buildings (b) and without the separate diesel generator buildings

Since the results showed, that the availability of the AM-DG during seismic events is mainly dominated by operator actions, additionally an alternative model of the basic human error probability (HEP) model has been applied called "improved HEP" model. Since seismic events dominate the CDF of Beznau with nearly 85 % of the CDF, the change would certainly effect the final CDF.

First, table 3 summarizes the results for the different plant configurations in terms of RAW and FV. In general, the results show, that the effect of the AM-DG is limited on the CDF due to the robust bunkered system and the new separate diesel generator buildings. Since the AM-DG is only designed for external events, the importance of this two major plant improvements covers the effects of the AM-DG. However, for NPPs without the bunkered system and/or without the new separate diesel generator buildings the importance is in the range of nearly one percent. The results of table 3 for the case without safety system (b) and (c) has only a limited validity, since the current model was slightly adapted to consider this configuration. However, a more detailed adaptation of the PSA model would probably show a higher importance. Even further, the configuration without (b) and (c) tries to model the plant as it was nearly 25 years ago. Hence, some other weaknesses of the old plant configuration dominate the results. However it seems to be plausible, that such weaknesses would have been improved, for example by enhancement of the spatial separation. Therefore it seems reasonable to assume an RAW of at least 1.01 and a RV of approximately 7 ‰ for this case.

Looking more into detail, one can realise that the AM-DG has an higher impact for the external events flooding or Loss of Offsite Power. The specific RAW value for the AM-DG for this events is in the range of 1.2. However, since the seismic CDF dominates the overall CDF, this effect is only limited visible in the results in table 3.

Table 3: RAW and FV for CDF of the new diesel generator for SAM on top of emergency building Unit 1 with the basic (standard) HEP model as well as FV for CDF with the improved HEP

NPP Condition	RAW (basic HEP)	FV (basic HEP)	FV (improved HEP)
(a) base case	1.0033	2.4 ‰	3.2 ‰
(b) w/o the separated DG buildings	1.0076	4.9 ‰	7.2 ‰
(c) w/o (b) and emergency building	1.0058	3.7 ‰	5.3 ‰

Table 3 also shows the effect of the different HEP-models in terms of FV. As is can be seen from this table, the HEP model indeed strongly effects the importance measure since (a) seismic is dominating the CDF and (b) the operator actions are important for the availability of the AM-DG in such cases. One has to mention, that the Swiss seismic HEP model introduced by the regulator seems to be conservative. Therefore realistically the RAW and FV values are larger as listed in table 3.

According to the latest Level 1 PSA the total frequency of core damage is lower than 10^{-5}/a. Based on the CDF history regarding the different plant configurations, it has been estimated, that the decrease of the CDF by 10^{-6}/a costs in the range of 100 Million Swiss Francs (CHF). Of course, this value grows with a declining CDF. Considering the costs of the installation of this AM-DG and the decrease of the CDF, the installation is cost effective for the Beznau NPP regarding the given value.

Since the configuration of the Beznau NPP is very specific, for other plants without the bunkered emergency systems or new separate diesel generator buildings, but with slight improvements especially, considering the electrical trains, the cost efficiency of the installation of the AM-DG increases significantly. Whereas the costs in Beznau were significantly lower than 1 Million CHF, assuming a CDF including seismic events in a range of 2 x 10^{-5}/a for another plant, the decrease of the CDF by the AM-DG would allow costs up to 10 Million CHF. Therefore for other plants, the installation of the AM-DG may be even more attractive to improve the safety of the plant in a quick way. Besides all the numerical effects, the AM-DG provides a diverse, robust and reliable power supply.

CONCLUSION

A new countermeasure for SAM at Beznau NPP in form of a base-isolation diesel generator system was presented. Conceptual design aspects including interdisciplinary issues as well as detailed information on design and construction phases of the base isolated structure were outlined. Further, methodology and results of seismic safety assessment were pointed out. Finally impact of the new AM-DG systems in risk reduction, in dependence of tree hypothetical NPP conditions were approximatively estimated. Results show, that the installation of the AM-DG is a cost effective measure to improve the safety of the plant. The result is even further valid for NPPs without the major upgrades, which Beznau carried out in the last decades. Besides the effectiveness, the installation requires lower formal efforts compared to major structural upgrades.

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