Appendix 1. Simplified seismic PRA example

The significance of various seismic hazard for nuclear safety can be studied by means of a simplified PRA model. In this model, PGA hazard curve is transformed into a set of seismic initiating events, $SE_1, SE_2, \dots, SE_n$, with different PGA values, $a_1, a_2, \dots, a_n$, and associated frequencies, $f(SE_1), f(SE_2), \dots, f(SE_n)$, taken from the PGA hazard curve.

The plant is represented by a representative set of typical SSCs (called hereinafter "component"), $X_1, X_2, \dots, X_m$, that can be damaged by the seismic initiating event and whose failure can cause a reactor core damage. The probability of a damage of a component is quantified by the common component fragility model (EPRI 1994) as follows

$$P(X_i | SE_j) = P(a_j; A_m, \beta_T) = \Phi\left[\frac{\ln(a_j/A_m)}{\beta_T}\right],$$

where a_j = ground motion input acceleration value of SE_j
A_m = median seismic capacity
$\beta_T = \sqrt{\beta_R{}^2 + \beta_U{}^2}$ = logarithmic standard deviation for capacity
β_R = logarithmic standard deviation for inherent randomness
β_U = logarithmic standard deviation for modelling uncertainty.

The values of the parameters A_m, β_R, β_U are specific to each component X_i, representing the component's fragility.

The component HCLPF (High Confidence of Low Probability of Failure) is

$$\text{HCLPF} = A_m \cdot \exp\{-1{,}645(\beta_R + \beta_U)\}.$$

Each component is assumed to fail independently of each other. Failure of any component X_i can lead to a core damage with certain probability, $CCDP_i$ (conditional core damage probability).

The core damage frequency of the seismic event SE_j can be quantified by

$$f(CD; SE_j) = f(SE_j) \sum_{i=1}^{m} P(X_i | SE_j) \cdot CCDP_i.$$

It is assumed that it is not relevant to include in this quantification scenarios where multiple components fail.

The overall seismic core damage frequency is

$$f(CD; SE) = \sum_{j=1}^{n} f(SE_j).$$

In this example, three different components are considered with fragility parameters listed in Table 1. These components can be considered typical SSCs representing a normal SSC, seismically sensitive SSC and seismically very sensitive SSC. Seismically strong SSCs have been excluded from the model since they do not give relevant insights in this context.

Table 1. *Fragility parameters (illustrative) of SSCs of the simplified seismic PRA example.*

Type of SSC	A_m	β_R	β_U	β_T	HCLPF
1. Normal SSC	0,61	0,22	0,2	0,2973	0,306 (~0,3)
2. Sensitive SSC	0,55	0,28	0,38	0,4720	0,186 (~0,2)
3. Very sensitive SSC	0,28	0,28	0,38	0,4720	0,095 (~0,1)

Three different seismic hazards are studied in this example. The base case is the reference case developed in the SENSEI project for the Loviisa site (denoted as LSenBM). The base case is modified upwards (LSenBMup)and downwards (LSenBMdown) so that the difference increases gradually as PGA is higher (factor 5 upwards/downwards for high PGA values. PGA curves are shown in Figure 1. It should be noted that the variations made to the hazard curve are purely synthetic and are *not* based on any sensitivity study performed in the SENSEI project.

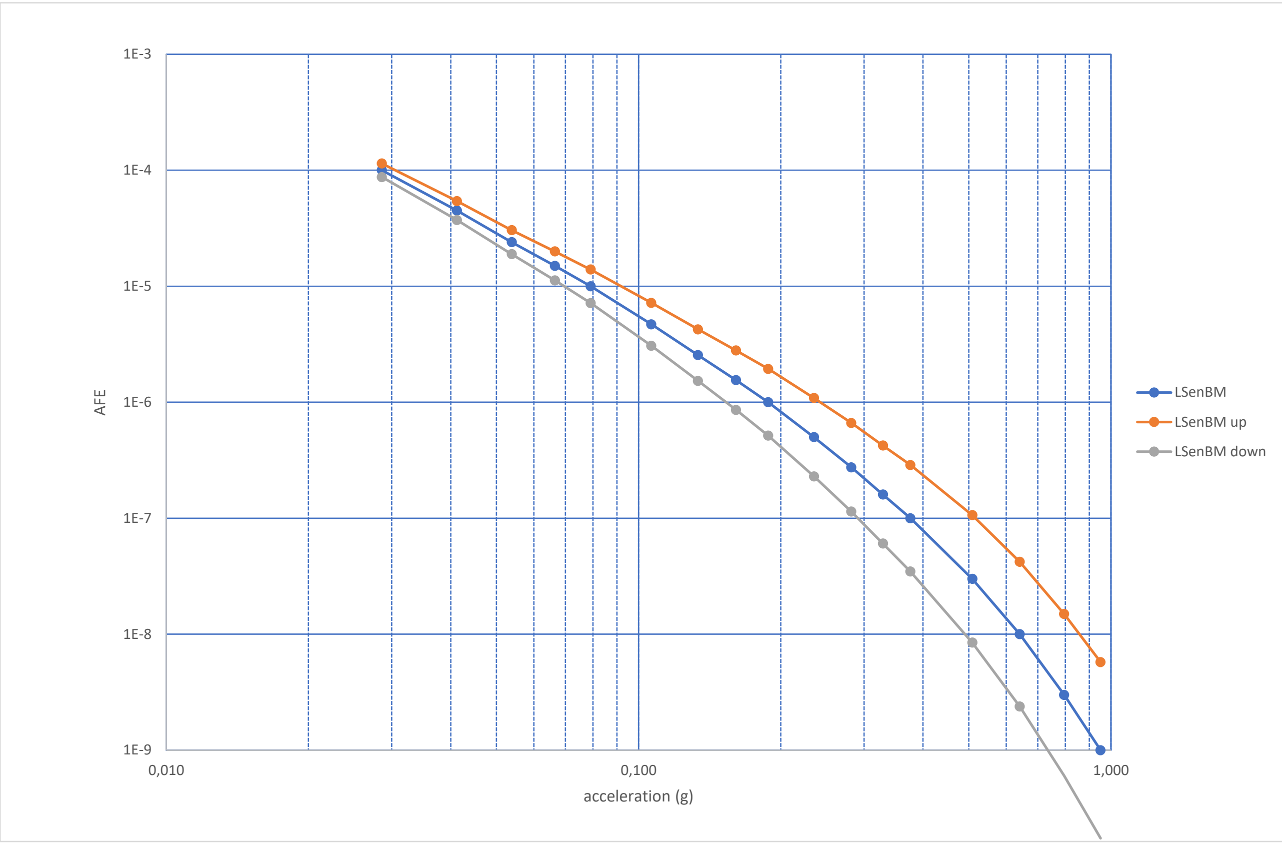

Figure 1. *Seismic hazard curves of the simplified seismic PRA example. The curves LSenBM up and LSenBM down are synthetic modifications of the base model curve, not calculated results in the SENSEI project.*

Three different conditional core damage probabilities (CCDP) are considered in the example:

- High: $CCDP = 1$,
- Medium: $CCDP = 0{,}2$,
- Low: $CCDP = 0{,}04$.

These cases represent rather large variation of CCDP values. However, it should be noted that in typical seismic PRAs, most CCDP values are lower than “Low” above. High CCDP values may appear, if a critical structure, e.g., a building is assumed to collapse or if a complete set of redundant SSCs performing a critical safety function is assumed to fail (kind of complete common cause failure).

Four sensitivity studies are performed:

1. Variation of fragilities — CCDP values are equal
2. Variation of CCDP values — fragilities are equal
3. Mixed variation of fragilities and CCDP values
4. Variation of seismic hazards — mixed variation of fragilities and CCDP values

Study 1. Variation of fragilities — CCDP values are equal

In the first sensitivity study, CCDP value 0,2 is assumed for all components, but the three components of the model have different fragilities, as given in Table 1. Seismic hazard is the base case LSenBM.

Figure 2 presents the density function of the core damage frequency for each component as well as for the total seismic core damage frequency. Clearly, the "very sensitive" SSC contributes mostly to the overall result (81 %), and most important seismic events corresponds with PGA values 0,1 to 0,5.

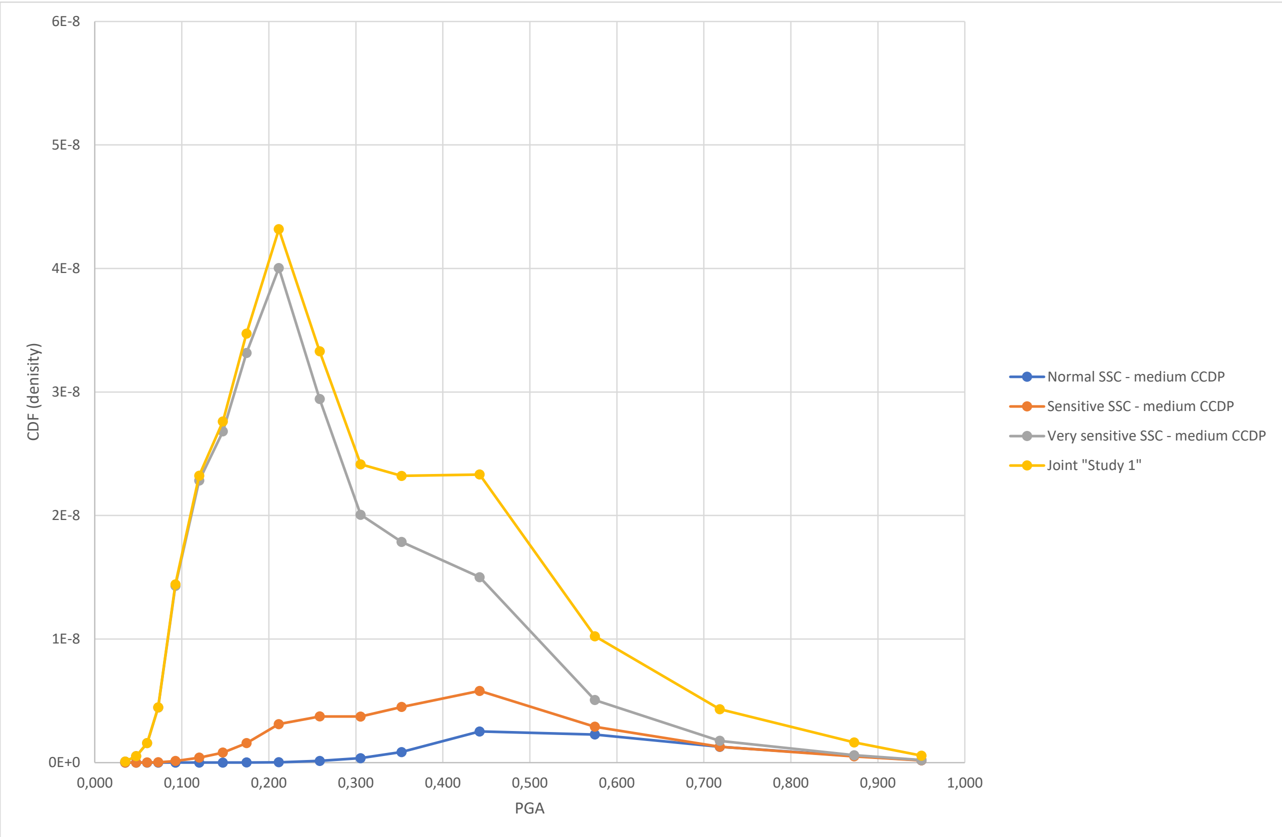

Figure 2. *Simplified seismic PRA study 1 (CCDP = 0,2): Variation of fragilities. The "very sensitive" SSC (gray curve) contributes mostly to the aggregated result (yellow curve). Most important seismic events correspond with PGA values 0,1 to 0,5.*

Study 2. Variation of CCDP values — fragilities are equal

In the second sensitivity study, fragility for a "sensitive" SSC is assumed for all components, but the three components of the model have different CCDP values (1, 0,2, 0,04). Seismic hazard is the base case LSenBM.

Figure 3 presents the density function of the core damage frequency for each component as well as for the total seismic core damage frequency. Clearly, the "high CCDP" SSC contributes mostly to the overall result (86 %), and most important seismic events corresponds with PGA values 0,2 to 0,6.

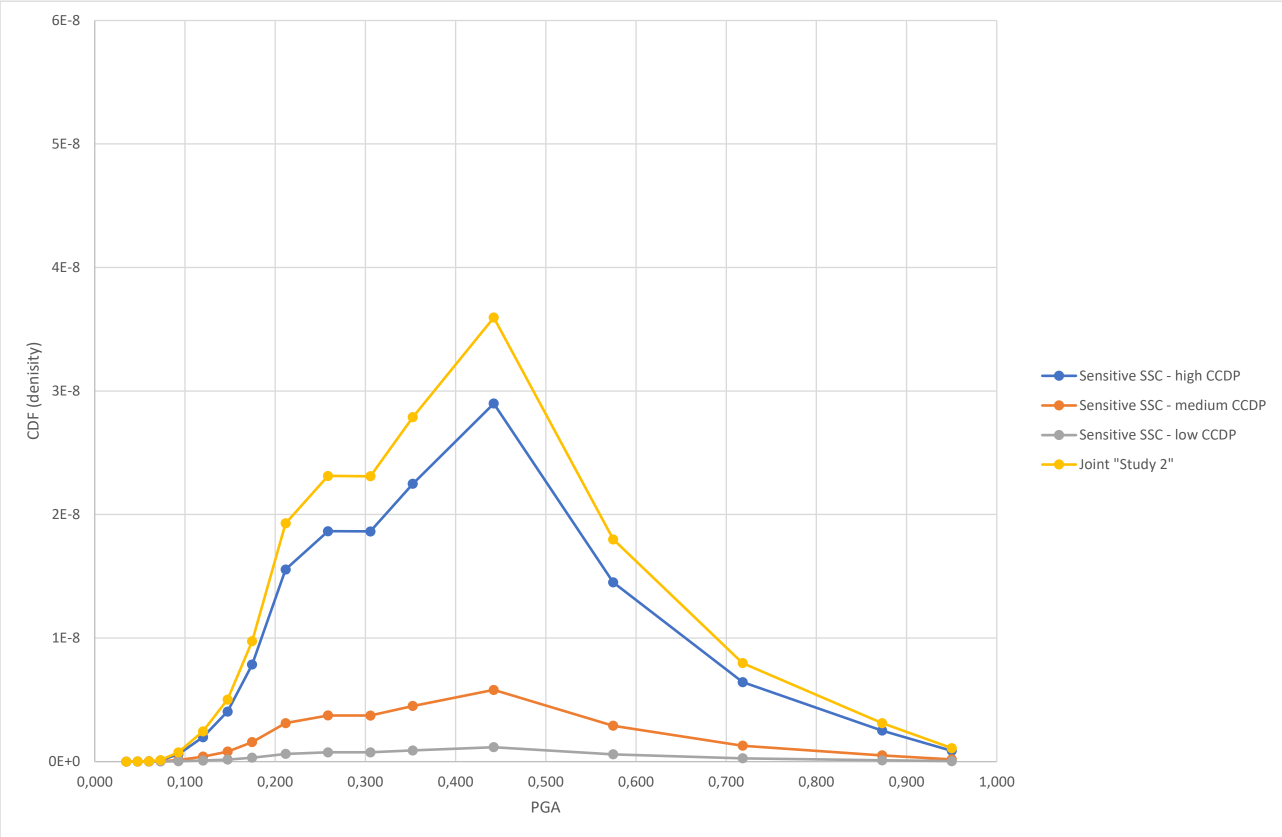

Figure 3. *Simplified seismic PRA study 2 (HCLPF ∿ 0,2 g): Variation of CCDP values. The "high CCDP" SSC (blue curve) contributes mostly to the aggregated result (yellow curve). Most important seismic events correspond with PGA values 0,2 to 0,6.*

Study 3. Mixed variation of fragilities and CCDP values

In the third sensitivity study, both fragilities and CCDP values are varied in such a manner that the most sensitive SSC has lowest CCDP value, and vice versa. Seismic hazard is the base case LSenBM.

Figure 4 presents the density function of the core damage frequency for each component as well as for the total seismic core damage frequency. In this study, all components have quite significant contribution to the overall core damage frequency. The range of important PGA values is somewhat broader than in study 2 — 0,1 to 0,7.

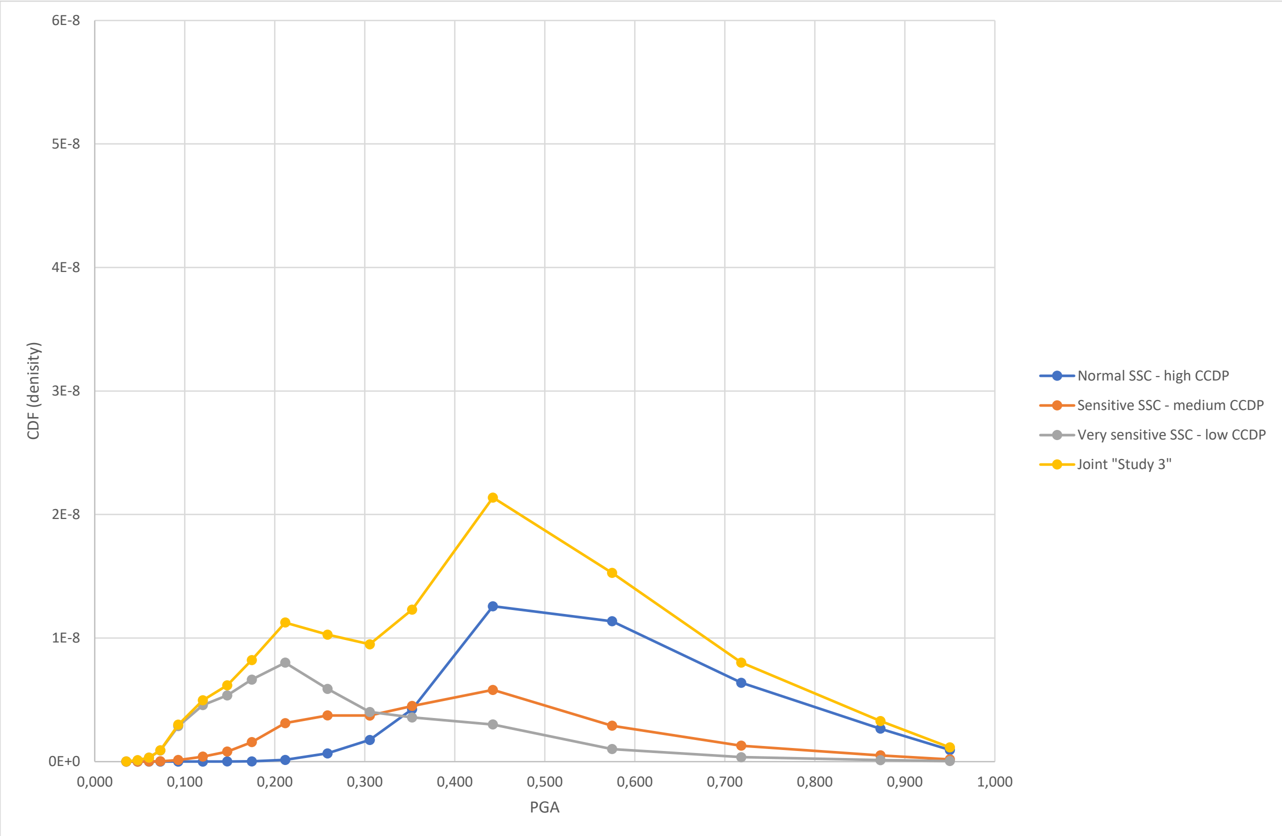

Figure 4. *Simplified seismic PRA study 3: Mixed variation of fragilities and CCDP values. All SSCs contribute to the aggregated result (yellow curve) at different PGA values depending on the sensitivity of each SSC.*

Study 4. Variation of seismic hazards — mixed variation of fragilities and CCDP values.

In the fourth sensitivity study, the fragilities and CCDP values of study 3 are assumed, but the base case seismic hazard LSenBM is varied upwards and downwards, as illustrated in Figure 1.

Figure 5 presents the density functions of the core damage frequency for each seismic hazard. The variation of seismic hazard seems to amplify the seismic hazard, but profile of the density function remains same.

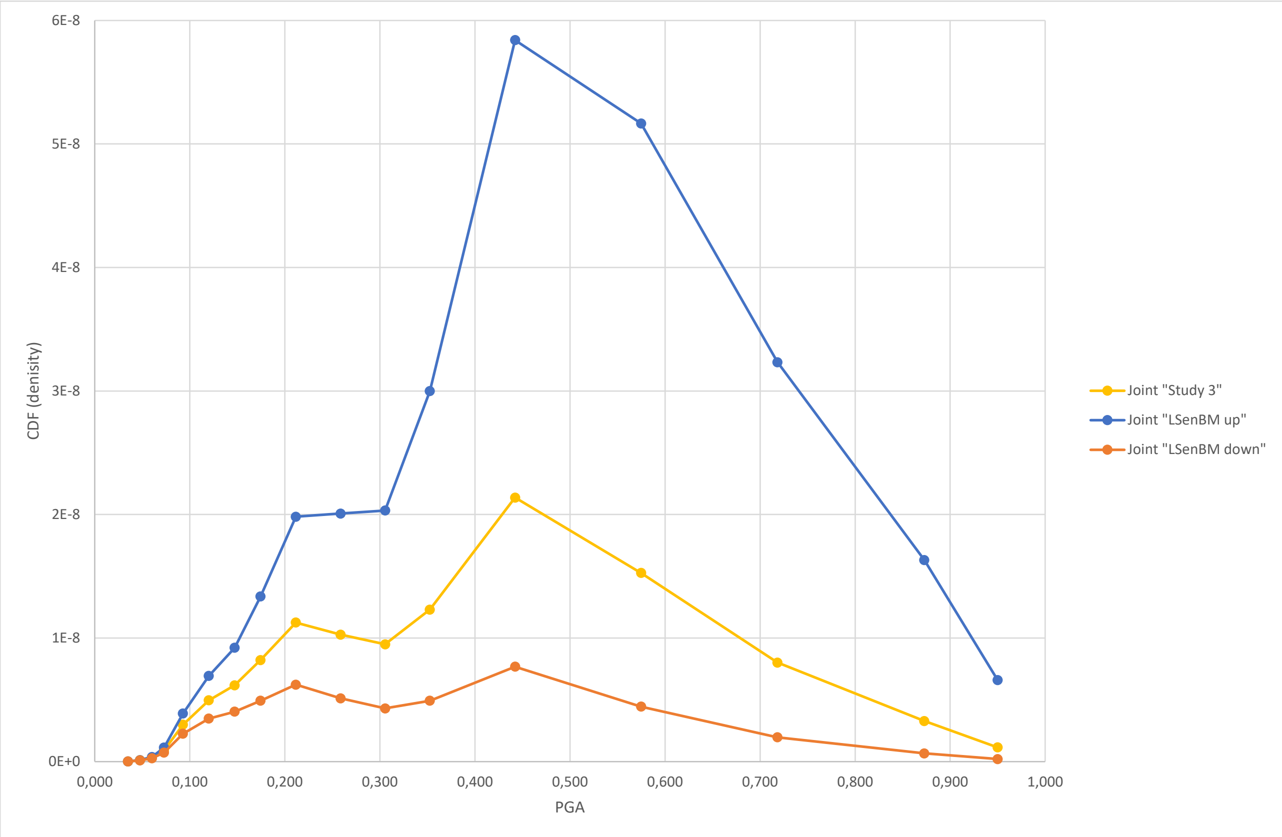

***Figure 5**. Simplified seismic PRA study 4: Variation of seismic hazards. Density functions of core damage frequency. Variation amplifies the seismic hazard but profile of the density function over PGA values remains about same. PGA values 0,3 to 0,9 contributes mostly to the aggregated result.*

Figure 6 presents the contribution of each SSC for each seismic hazard case. When the seismic hazard becomes higher (LSenBMdown -> LSenBM -> LSenBMUp), the relative importance of the "Normal SSC – high CCDP" increases from 30 % to 51 %, while relative importance of the "Very sensitive SSC – low CCDP" decreases from 46 % to 25 %.

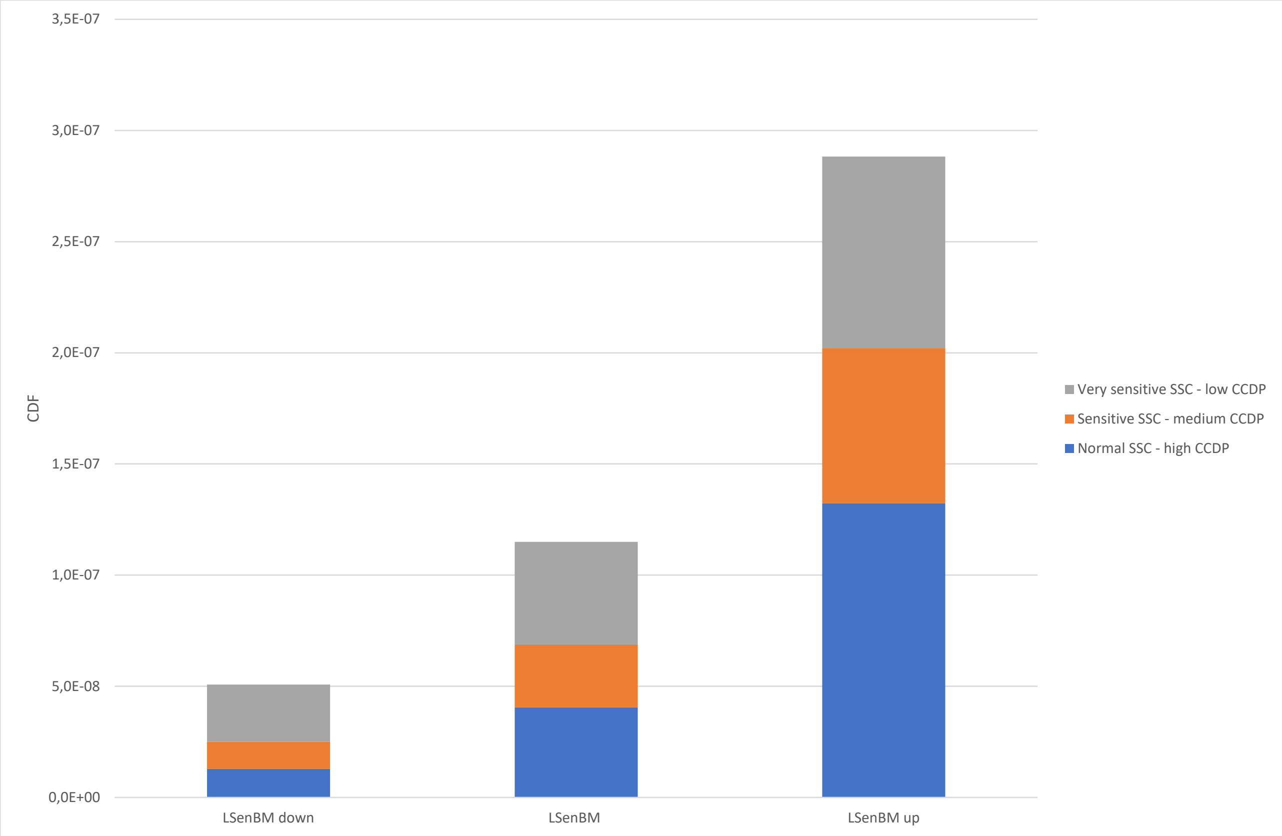

Figure 6*. Simplified seismic PRA study 4: Variation of seismic hazards. Core damage frequency contribution of each SSC. When the seismic hazard becomes higher, the relative importance of the "Normal SSC – high CCDP" increases, while relative importance of the "Very sensitive SSC – low CCDP" decreases.*

Conclusions

The following observations can be made from the simplified seismic PRA example:

- Seismic events around PGA 0,2 to 0,6 g are the most important regarding seismic risk. They have AFE in the range of 1E-7/yr to 1E-6/yr.
- Core damage frequency values 1E-7 per year of this example are low and typically would not contribute much to the overall core damage risk of an NPP. However, in the seismic scenarios, the conditional probability of large or early release can be high. From the external release risk assessment point of view (level 2 PRA), it can even be meaningful to put effort in the estimation of seismic hazards at PGA levels 0,5 or above.

It should be noted that in the above calculational example the very sensitive SSC had low CCDP. If there are very sensitive SSC with high CCDP their contribution to core damage frequency would be very large and the hazard at PGA 0,1g – 0,2g would also be quite important. In seismically designed NPP units there should be no such SSCs. However, in older units, which have not been seismically designed, some such components have been identified.

References

EPRI (1994). Methodology for Developing Seismic Fragilities, EPRI TR-103959. EPRI, Palo Alto, CA.