Analysis of precursor accidents in nuclear power

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Abstract: Nuclear accidents are rare but costly, and realistic figures for the risk of nuclear power plants are needed. The analytical framework of PSA has developed substantially, but is not without defects, notably when quantifying risk at an absolute overall level. It is therefore best complemented with statistical experience. A statistical precursor based assessment of the core damage frequency (CDF), primarily at Western second generation units, is done - making use of elements of PSA. This indicates major improvements since Three Mile Island, and a more recent CDF similar to current reported PSA values. Allowing for extremely costly major accidents, this CDF implies an accident externality still smaller than that of fossil fuels, and similar to wind and PV. Taking this admittedly rough analysis as a promising indication, we propose further development of precursor-based assessment and more intensive use of our comprehensive database on nuclear events, in particular to create generic/harmonized and simplified PSA models and perform wide-scale precursor analysis to obtain order-of-magnitude conditional CDF estimates. In our view, such information can form the basis to better answer "big-picture" questions about the overall absolute risk level of nuclear power plants including the external cost of nuclear accident.

Keywords: Database, Nuclear power incidents and accidents, learning from experience.

1. INTRODUCTION & REASONING

Understanding and improving safety are crucial – perhaps existential – issues for the nuclear sector. Quoting the IAEA, "nuclear safety requires a continuing quest for excellence", supported by the technical principle of learning from safety research and operating experience [1]. It is thus clear that all relevant empirical data and scientific techniques should continually be brought to bear. This is relevant for all operating fleets, regardless of long-term plans for nuclear facilities, including power plants (NPP).

In view of more than 400 reactors worldwide and 15'000 accumulated reactor-years of experience, nuclear accidents are rare but costly. A common opinion is that, if the external cost of nuclear accidents were included in the price of electricity, then nuclear power would become economically unfeasible. A "negative learning rate" has even been claimed, on the basis of increasing capital and operating costs. Because one should not make decisions that are crucial for society on the basis of opinions or unsubstantiated claims, it is essential to be able to provide realistic evidence-based figures for the risk of nuclear power from a safety and cost perspective. Such figures should then be used for regulation, for the balancing of the energy portfolio (considering accident externalities, among others), and for public acceptability.

Due to the rare nature of severe plant states -- like core damage and large early releases -- the ability to assess risk on a purely statistical basis at systems level is very limited. Affirmative relief has been provided by PSA, a systematic approach that makes use of statistical information at the more basic components level and, through an analytical framework, derives system level behavior on a plant and site specific basis. It has become the primary framework for studying and regulating safety within the nuclear community, complementing deterministic analyses. Level 1 corresponds to the assessment of the risk of core damage accidents, being quantified by the core damage frequency (CDF) per reactor-year [2]. Level 2 characterizes the release of radioactive substances from the reactor building to the environment in the event of an accident (full "source term" or at least large early release frequency, LERF), in order to develop accident management strategies and identify potential design weaknesses in the containment system design and performance [3]. CDF and LERF are regarded as representative surrogates to steer the design and operations of systems towards a high safety level and achieving quantitative and qualitative safety goals. PSA Level 3 evaluates the impact of such releases on public health and the environment, as well as direct costs, and is used mainly for academic purposes and emergency planning, in particular [4,5]. To demonstrate compliance with international and some national guidelines, CDF of not more than 10^{-4} and 10^{-5} per reactor-year are required for "old" and "new" plants, respectively; LERF should be significantly smaller, e.g., by one order of magnitude.

PSA – in particular levels 1 and 2 – has been successful in identifying vulnerabilities (weaknesses) and possible improvements in plant safety through design and operation, as well as in evaluating the completeness and balance of the design for safety. However, even the most advanced current (full scope high quality) PSA are still subject to major developments and acknowledged deficits [6-8] -- in particular at level 3, being a key element needed to characterize risk. Perhaps the most fundamental issue is that one cannot prove (mathematically) that the set of included sequences is complete. For instance, thirty percent of accident precursor events (of non-negligible significance), in the US between 2000 and 2010, were not captured by the NRC PSA models [9]. Further, in a study of experienced events, many found the need to go beyond high quality PSA to sufficiently describe the event [10]. In other terms, the main value of PSA is not in providing absolute figures at level 3, but relative figures at lower levels, to enable comparison of design and planning options. Thus, PSA is mainly thought of as a plant-specific platform for technical exchanges on safety matters between regulators and the industry, among peers, and between designers and operators. However, for lack of a better source, PSA information is often relied on for decision making within the public and corporate sector, who need sound risk estimates in absolute terms.

2. EXTENDING PSA TO A HYBRID, PRECURSOR BASED APPROACH

A promising hybrid approach, taking elements from PSA but directly using operating experience, is *precursor based assessment*. A (core damage) precursor is an event in which core damage did not occur, but would have if additional failures and/or initiators had occurred. Fukushima Daini in 2011 provides a good example of a true "near-miss"*. Precursor analysis takes place within many countries. Notably, the US NRC Accident Sequence Precursor Program (ASP) published results openly [11]. And it has many attested uses [12], e.g.,: 1) identification of safety issues that might have been overlooked/underestimated within PSA; 2) focused consideration of complex events or combinations of events; 3) confirmation or monitoring a level of safety, including trending over time, exploiting the large sample of precursors relative to the few bona fide core damage accidents. We call *precursor based assessment* the combined use of historical precursor events to estimate/compare with CDF, and possibly LERF, and which put less emphasis on the individual events.

Here, we perform a precursor based assessment to compare historical operating experience with the typical range of quoted CDF values. This relies on a pooling of experience across multiple reactors. Some may criticize this pooling, based on a belief that each unit is "incomparably unique to others, and to itself over time", which is consistent with the need that PSA be site and unit specific, as well as regularly updated – even "living"— for regulatory purposes. However, the majority of existing units belong to the same generation, with a limited number of design classes, from a limited number of vendors, etc.; they are exposed to similar types of dominant risk (external hazards, LOCAs, transients including loss of preferred power or ultimate heat sink, etc.). The commonality is further demonstrated when "history repeats" in the case of forerunner events, existing for all major accidents. This change in perspective has two aspects: the first is going from (site/unit-) specific to a generic perspective (at least for a relatively similar pool of reactors). The second is from an objective to characterize relative risks in great detail, as required by the regulator, to a focus on a more simple and direct quantification of the absolute risk level. This means that estimates of the conditional core damage frequency (CCDF),

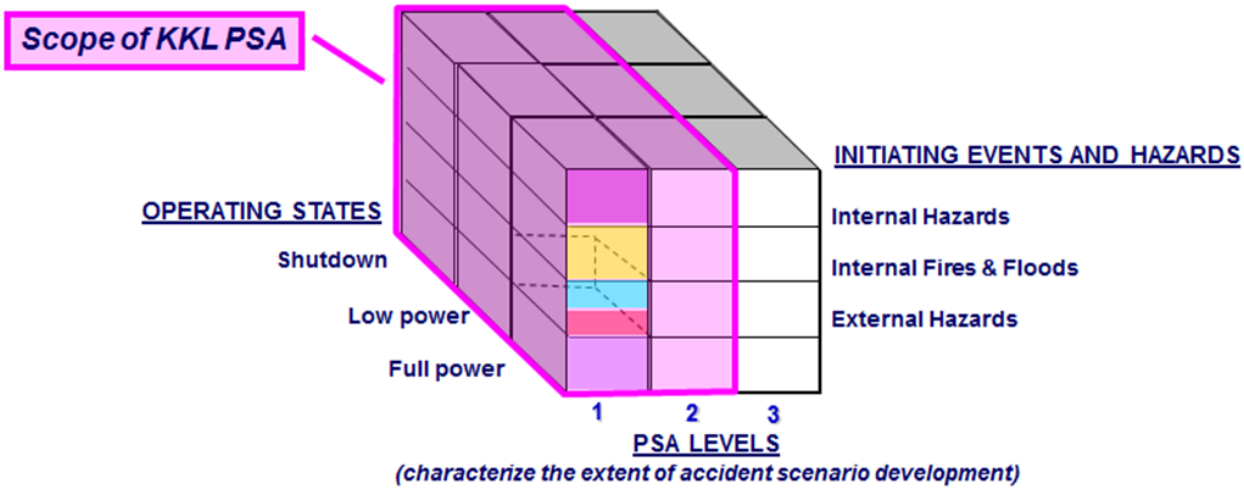
* Fukushima-Daini, neighbor to Daiichi site, where the 2011 earthquake and tsunami also caused major flooding. Unlike at Daiichi, one of the four external power lines remained, allowing the plant operators to maintain control, and due to outstanding accident management, a core damage accident was avoided.

quantifying the individual precursors, can be approximate – i.e., generic, “order-of-magnitude” estimates.

Indeed, looking to existing PSA, despite international and national guidelines and best practices, there is a large diversity in the methods and quality of PSA, especially from country to country, and little in the way of a systematic and transparent explanation of the differences. In particular, whether and how internal and external triggering events, human factors, and common cause failure are treated, have a large impact on quality and results. Among other things, this makes the comparison of results of different PSA, and precursor analyses, difficult.

Furthermore, models have become very detailed, unruly in size and complexity, and opaque to the extent that only highly specialized experts can attempt to fully understand them, as illustrated in Figure 1 and Table 1. E.g., at KKL (in Switzerland) the PSA contains: >200 initiating events, millions of partially complex event sequences, and more than 10k pages of documentation. The size also forms a substantial over-head/inertia making advances/modernization difficult, and existing standards cause reluctance to change. Some attempts at modernization have been introduced: e.g., The Open PSA Initiative[†]. However, PSA practice is still in its “first generation” (based on fault/event trees constructed at the most basic logical level, and basic human reliability analysis), with PSA from different plants being difficult to compare, partially due to proprietary (not open) software from vendors. Clearly, there is room for improvement in terms of open standards (transparency, consistency, etc.), as well as for *usability*.

Figure 1: Representation of KKL PSA scope. Illustrating the complexity of event trees generated within a full scope, high quality PSA; excerpt from the PSA for the Swiss Leibstadt NPP (KKL).



Here, rather than concentrating on improving existing PSA, we focus on the questions: 1) Can simplified and harmonized/generic PSA models enable large scale precursor assessment, providing a basis for order-of-magnitude risk assessments that better address big picture concerns about risk in the nuclear sector? And 2) Can relaxing some detail and precision requirements allow for a more complete/ big-picture view and comparisons of CDF estimates?
To demonstrate the potential of this approach, we first perform a precursor-based assessment of the CDF, and of apparent safety improvement in the US, as well as a rough comparative safety assessment for four regions spanning all major nuclear nations. Afterwards, objective, assumptions, and approaches are discussed for the development and wide-scale application of order-of-magnitude generic simplified precursor analysis.

Table 1: Summary of KKL PSA.

†. https://open-psa.github.io/joomla1.5/index.php.html

Module	**Area**	**No. of Events Modelled**
Initiating Events	Loss of Coolant Accidents	67
	Transients	28
	Special Initiators	20
	Internal Fires	66
	Internal Flooding	25
	Turbine Missile	1
	Earthquakes	26
	Lightning strike	1
	Sun storm	1
	Aircraft crashes	3
	Extreme winds	3
	Tornado	3
	Heavy rain	1
	Service water intake plugging	1
Component Reliability	Failure Modes	28
	Component Groups	43
	Failure Rate Parameters	180
	CCF Groups	350
Plant Operating State	POS Groups	12
System Modelling	Frontline Systems	11
	Secondary Systems	7
	Containment Systems	4
	Support Systems	7
	No. of Fault Trees	4260
	No. of Basic Events (incl. human errors and maintenance unavailabilities)	21730
Accident Sequence Modelling	Event Tree Templates	14
	No. of Event Trees (includes Level 1, Level 1+ and Level 2)	309
	Function Events in Level 1, 1+, 2	65, 11, 32
	Core Damage States	30
	Plant Damage States	2342
Human Reliability Analysis	Actions of different categories	142

3. PRECURSOR ANALYSIS

Precursor analysis is a use of PSA applied to specific events. In other words, it is a conditional PSA, where each event is quantified by a conditional core damage probability (CCDP). There are two types of events that, in some combination, form a precursor: (1) initiators and (2) vulnerabilities/degradations leading to un-availability of safety relevant systems, potentially leading to core damage in the presence of certain initiators. Both types can be mapped onto a PSA model and the CCDP computed. Precursor analysis is done by many national regulators and technical support organizations, such as IRSN in France or GRS in Germany. Reported figures, methods, and objective vary, making comparison difficult. To a large extent they rely on use of plant-specific PSA. For instance, the US NRC SPAR models[‡] are complicated and plant-specific, with primary use being PSA regulation, and precursor analysis being secondary.

It is common to combine the individual CCDP to provide an indicator of the real-time CDF, or simply interpreted as some kind of safety index. The basic idea is that, in PSA, one sums over all hypothetical initiators and chains, weighted by their probabilities. In a precursor based assessment, one sums over

‡ https://www.nrc.gov/docs/ML1029/ML102930134.pdf

the CCDP for the precursor conditions observed, approximating the CDF. This can be formalized as follows. For N possible sequences, $\mathrm{X}_i = 1$ if that sequence leads to core damage, and $\mathrm{X}_i = 0$ otherwise. Sequence X_i requires an initiator/condition, $\mathrm{C_i} \in \{0,1\}$, in the sense that,

$$\mathrm{CCDP_i}=\Pr\{\mathrm{X}_i = 1 \mid \mathrm{C_i} =1\}, \text{ and } \Pr\{\mathrm{X}_i = 1 \mid \mathrm{C_i} =0\}=0.$$

The expected number of core damages (CD) and its approximation based on a sample of precursors are then,

$$\mathrm{E[CD]}=\mathrm{E}[\textstyle\sum_{i=1}^{\mathrm{N}} \mathrm{X}_i]=\sum_{i=1}^{\mathrm{N}} \Pr\{\mathrm{X}_i = 1, \mathrm{C_i} = 1\} = \sum_{i=1}^{\mathrm{N}} \mathrm{CCDP}_i \Pr\{\mathrm{C_i} = 1\} \approx \sum_{i\in S} \mathrm{CCDP}_i \ ,$$

where S is the set of observed precursors. One can then divide this by the number of reactor-years of operating experience to obtain an estimated CDF. Uncertainty quantification requires a probabilistic model. Here the object is a *compound random variable*: the number of precursor events is suitably treated as a Poisson random variable, and the CCDP values are independent realizations of a random variable taking values between zero and one.

However, there are certain issues regarding what constitutes the condition– e.g., it need not be simply an initiating event from the PSA, but rather the CCDP could be adapted to broader condition. The logic of precursor analysis is that "just because core damage did not result does not mean that it could not have happened". Similarly, "just because core damage happened does not mean that, under the same circumstances, it would happen every time". E.g., at TMI, the pilot operated relief valve could have closed, however, in the NRC report, a CCDP of 1 is given**Error! Bookmark not defined.**. But using a CCDP of 1 in a precursor based assessment will result in an over-counting. At the same time, a binary core damage state is reductive, as TMI could have been worse, therefore suggesting precursor analysis at the LERF level.

4. COMPARING PSA WITH EXPERIENCE BY PRECURSOR BASED ASSESSMENT

4.1 Quantification of learning & the accident externality

A CDF of 10^{-5} per reactor-year predicts that an average of 0.15 events should occur during 15'000 reactor-years of experience, giving an 86% probability of zero core melting events during that time with a Poisson probability. However, the major historical accidents at commercial nuclear power stations include five bona fide core damage accidents[§]: Fukushima-Daiichi, units 1 – 3, 2011; Chernobyl-4, 1986; and TMI-2, 1979. This yields a global historical average core damage frequency (CDF) of $3.3\text{x}10^{-4}$ per reactor-year, with 95% confidence interval (10^{-4}, 10^{-3}). Limitations of these estimates are clear – the confidence interval of the estimated CDF spans an order of magnitude, and this number neither applies to a specific site, nor to the current time, as safety has improved in many concrete ways since, e.g., the Three Mile Island (TMI) major accident of 1979. Further, it is subject of discussions whether Fukushima should be counted as three and Chernobyl should be included at all.

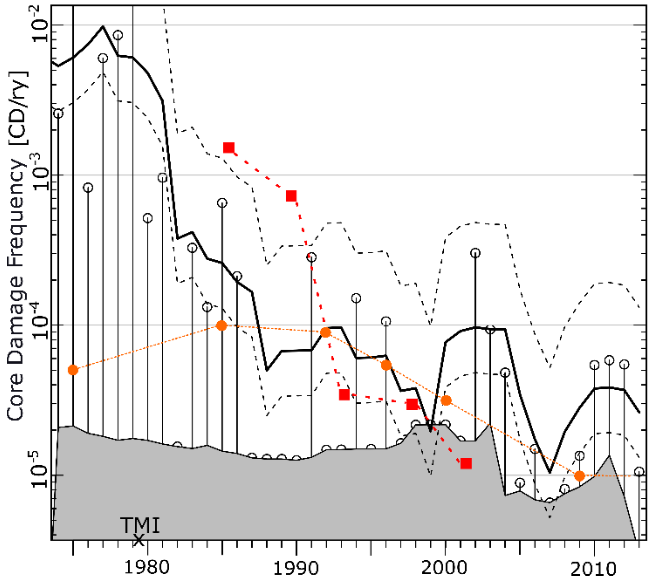
Here, we perform a more specific empirical test of PSA CDF figures via precursor based assessment, with methods described in Section 4. Importantly, this broader sample enables the study of the evolution of the CDF over time, as summarized in Figure 2 for the US fleet. A high CDF prior to TMI is assessed, after which a drop of two orders of magnitude took place, attributed to retrofits and learning arising from the NRC TMI Action Plan [13]. This roughly agrees with the analysis by the NRC, who estimated a level of $2.3\text{x}10^{-3}$ for 1969-1979 [14], and similarly for the Swiss Beznau plant[**].

[§] A common definition is a melt of 1% core inventory, for a typical commercial unit, beyond which fall-out and acute health effects become a possibility. See discussion in IAEA. Low Level Event and Near Miss Process for Nuclear Power Plants: Best Practices. IAEA, Safety Reports Series No. 73 (2012)

[**] For instance, the big drop in CDF observed in Figure 2 from pre- to post- 1990 was due to the 1/2 Billion USD invested in bunkered safety systems.

Insights from this analysis include clear evidence of learning and improvement: a meaningful reduction of CDF is demonstrated, coinciding with capacity factors growing from 60% in the 1980s to 80-90% since 2000[††]. Also, the assessment supports current PSA CDF estimates for US plants below 10^{-4}, and perhaps as low as 10^{-5} given low external hazards and superior safety systems. However, relevant limitations include that this assessment is not plant specific, assumes that the PSA based precursor analysis is complete and representative, and may not fully capture the risk of rare beyond-design basis accidents (BDBA).

Figure 2: Precursor based assessment of CDF. Reduction in estimated CDF combined with quoted PSA CDF values. The black line gives the CDF estimate based on US precursors, with 90% confidence bands; and the hollow dots give the same estimates done on annual windows. The grey area gives the contribution to the precursor assessment from long-term vulnerability precursors. The red square points give the PSA CDF results for the two Swiss Beznau units including retrofits and the orange dots give the mean PSA CDF results for the US fleet [14].



To comment on what this means for an accident externality, we first take a conservative CDF value, for a Western Gen II unit to be 10^{-4}. Next, rough estimation of the full cost to society of nuclear power accidents [16] indicates that a single core damage accident, with the possibility of a large release, gives a mean overall costs to society on the order of 100 Billion USD. Taking the product of frequency and severity, the pure risk is USD 10 Million/reactor-year, giving an externality of about 0.1 USD cents/kWh, for a unit with annual generation of 10 TWh/reactor-year. This puts the accident externality on a similar order to renewables, and several times smaller than that of fossil fuels [17]. However, the risk is *heavy-tailed* -- being extremely rare with severe consequences primarily on the country where the accident takes place. It is therefore important to not only continue to decrease CDF, but to lower the potential severity of accidents to the greatest extent possible.

4.2 Comparative assessment

On a comparative note, a rough precursor based assessment of CDF is done for four different regions[‡‡]: 1) the US, 2) North and Western Europe, plus Canada (NWE), 3) Japan, Korea and India (JKI), and 4)

[††] e.g., https://www.nei.org/Knowledge-Center/Nuclear-Statistics/US-Nuclear-Power-Plants/US-Nuclear-Capacity-Factors

[‡‡] Unfortunately, we do not have data for China. EE is “Eastern Europe”, including Russia, former USSR, Armenia, Bulgaria, Hungary, Romania, Slovakia, Slovenia, and Ukraine. This is a rather conventional grouping, which has some justification based on relatively common technology and governance/regulation. However, this “clustering” of countries has not been tested here, and within the clusters not all national fleets and units are the same.

Eastern Europe (EE). Note that this grouping is somewhat conventional but has not been rigorously tested via statistical cluster analysis. Aside from the US, precursor CCDP (conditional core damage probability) values are very imprecise, being based on a mapping [18] from INES (International Nuclear Event Scale) scores compiled in our database [16]. The results are summarized in Table 2, indicating:

- For the full operating history, NWE has had a significantly lower CDF than the US. However, post-TMI, the estimated levels are similar, around 10^{-4} per reactor year.
- For Japan, Korea, and India, Japanese external BDBA-triggered events (incl. Fukushima, 2011 and Kashiwazaki, 2007) drive up the CDF, which would otherwise be similar to the US & NWE.
- For Eastern Europe, even without Chernobyl, the estimated CDF is around $5x10^{-4}$. However, it is likely that improvements have taken place, not captured by this historical figure.

Table 2: INES and precursor-based CDF by region. For the four regions, the estimated historical core damage frequency (and for US* from 1980 onwards) are given by the estimated mean and 0.1 and 0.9 quantiles, scaled by 10^4. For the US, the contribution to the estimate for TMI (2.3) is given separately, as well the Fukushima, 2011 related events (Four INES=3 at Daini and three INES=7 at Daiichi) for JKI, and Chernobyl for the EE category. The INES columns give the counts of INES scores corresponding to the precursor events, taken from our database.

Region	Reactor years	INES 0+1	INES 2	INES≥3	CDF x 10^4
US	4’300	245	87	15	2.3+{1.4, 2.5, 3.6}
US*	3’440	245	75	7	{0.4,0.6,0.8}
NWE	5’500	86	78	7	{0.7, 1.1, 1.5}
JKI	2’800	57	13	12	12.1+{0.7, 1.4, 2.1}
EE	2’300	12	27	15	4.3+{3.0, 4.8, 6.1}

5. HARMONIZED, SIMPLIFIED MODELING FRAMEWORK

5.1 Objectives and key assumptions

The aim of developing a simplified modelling framework is threefold:

- to provide the basis for a broad assessment of the absolute risk from safety and cost perspective of nuclear power,
- to develop and apply a harmonized, simplified methodology to allow for additional insights, comparative assessments and identification of trends over time– as exemplified in the previous analysis, and
- to overcome the practical difficulty of applying the corresponding plant-specific models to each event.

Further we strive for a more rigorous probabilistic definition of precursors to avoid “double counting” and define consistently what constitutes the condition of the precursors, beyond which the sequence is given a probability less than one.

The use of PSA for regulatory purposes, e.g., estimation of sufficiently precise plant-specific CDF, requires plant specific information about the design and operation, upgrades, data and site conditions, as well as plant specific models. However, we assume that the provision of order-of-magnitude generic CCDF can be based on generic information (plant layout) for a reactor type (PWR or BWR) and reactor line (vendor) and related design features and, notably safety grade frontline systems and associated support systems. This is justified by the fact that Western countries and industries applied roughly the same safety principles as well as operational rules and regulatory requirements. Further, we assume that generic data are available and sufficient to derive generic probabilities and CCDF, respectively.

In the NEA workshop [10] no optimum level of detail for the models could be prescribed, perhaps in part due to varying objectives and requirements. Interestingly, several participants experienced the need to improve or to extend the existing PSA model for a correct modeling of a particular event. We assume that the current PSA models can be simplified to having a limited number of events and high-level hierarchical functional blocks such as reactor shutdown, decay heat removal, feed-and-bleed, containment isolation and accident management measures. We further assume that initiating events can be grouped (LOCA, transients, external events) and clustered (e.g., three types of LOCA, transients due to failures of the secondary cycle or loss of preferred power) to some extent.

Finally, we expect that harmonized, simplified models allow for necessary alignment with plant specific models and sequences, where available, to gain big picture insights. e.g., to check whether precursor event sequences are covered by full-scope PSA models and to identify and explain differences between PSA in different countries.

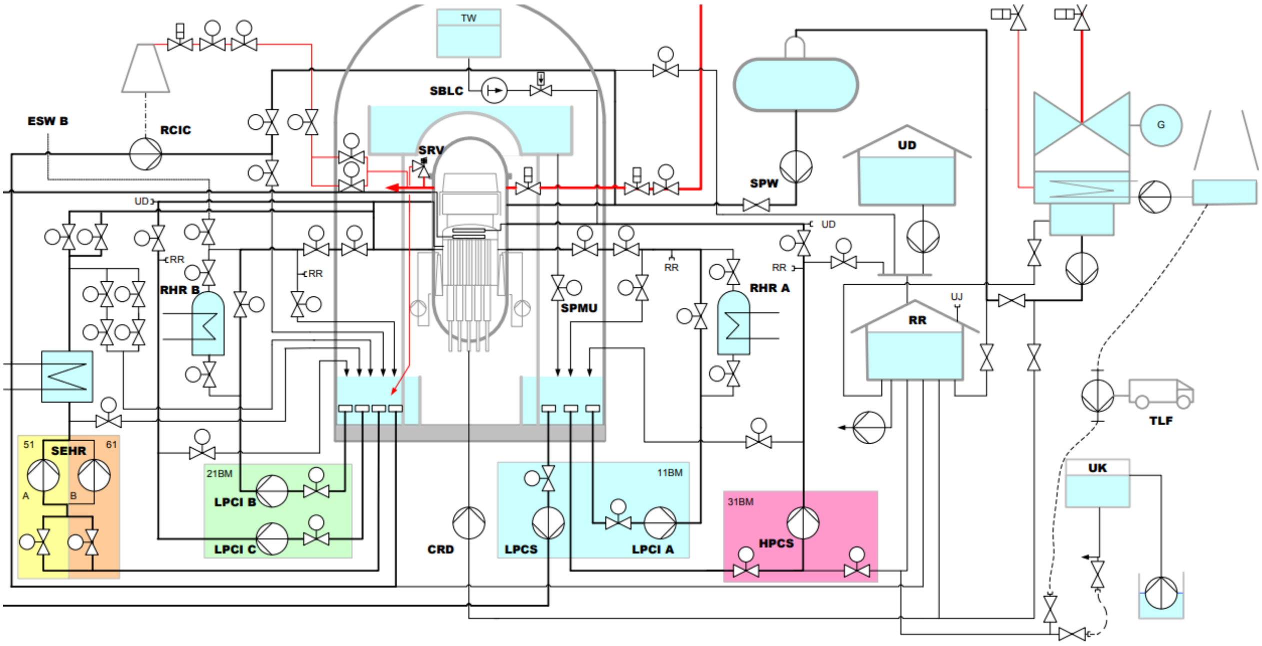
5.2 Approach

We will first restrict to the construction of simplified PSA models for two or three predominant western designs of PWR operating in countries with large fleets and broad coverage of events in our database. Candidate designs are US Westinghouse PWR 4-loops, French N4 and German Siemens Konvoi. Representative BWR designs are foreseen to follow in a second phase, making use of experience gained in the first phase. We will first focus on grouped and clustered internal initiating events – such as loss of coolant accidents, transients and special initiators—and excluding internal fires and floods and external hazards. We will distinguish between different operational states, i.e. full power, reduced power and shut down, reducing power and start up, maintenance and repair.

We will explore the usefulness of event trees simplified to a limited number of functional events at the upper hierarchical level and allowing for zooming in more detailed models (fault trees) for key front line and related support systems, see Figure 3 for illustration of main safety functions of a representative BWR.

The precursor analysis will be done for the more than one hundred candidate precursor events contained within a comprehensive database [16], to provide order-of-magnitude CCDP values, for PWRs to start with and BWRs to follow, each of representative Generation II Western designs.

Figure 3: Overview of the main safety functions of a BWR to be modelled as functional blocks. Dependencies are established but not shown here.



6. CONCLUSIONS

To support reliable assessment of the absolute risk of nuclear power, we propose precursor based assessment, making use of statistical experience as well as elements of PSA in an integrated database. In particular, it was demonstrated that pooling precursors from multiple units is useful for analyzing trends in safety [19], comparing with quoted CDF from PSA, and comparative purposes. This calls for a wide scale precursor analysis, providing order-of-magnitude, generic CCDP figures, to enable further and more precise precursor based assessment. Rather than having site-specific operational and regulatory objectives, allows for simplified and generic PSA models to be used. The need and key elements of the development and deployment of this were outlined and a first approach on a harmonized, simplified modeling approach based on functional blocks, complemented by more detailed fault trees at the lower hierarchical level was presented.

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