DEVELOPMENT OF A FULLY COUPLED, ALL STATES, ALL HAZARDS LEVEL 2 PSA AT KKL

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This paper describes the development process, the innovative techniques used and insights gained from the latest integrated, full scope, multistate Level 2 PSA analysis conducted for the Leibstadt Nuclear Power Plant (KKL), Switzerland. KKL is located in northern part of the country, close to the German border beside river Rhine. It is a modern single-unit General Electric Boiling Water Reactor (BWR/6), Mark III Containment, with power output of 3600MW$_{th}$*/1200MW*$_e$*, highest among the five operating reactors in Switzerland.*

A Level 2 Probabilistic Safety Assessment (PSA) analyses accident phenomena in nuclear power plants, identifies ways in which radioactive releases from the plant can occur and estimates their pathways, magnitude and frequency. This paper attempts to give an overview on the advanced modelling techniques that have been developed and implemented for this study, with the aim of systematizing the analysis and modelling processes, as well as complying with the relatively prescriptive Swiss requirements on PSA.

The analysis provides significant insights into the absolute and relative importances of risk contributors and accident prevention and mitigation measures. Thanks to several newly developed techniques and an integrated approach, the study exhibits a high degree of reviewability and maintainability, and transparently highlights the most important risk contributors to LERF (Large Early Release Frequency) with respect to initiating events, components, operator actions or seismic fragilities.

I. INTRODUCTION

A Level 2 Probabilistic Safety Assessment (PSA) analyses severe accident phenomena in nuclear power plants, identifies ways in which radioactive releases from the plant can occur and estimates their pathways, magnitude and frequency.

In Switzerland, each nuclear power plant has to maintain and update its Level 2 PSA on a 5 years' basis according to the technical requirements of Swiss regulatory guide ENSI-A05 (Ref. 1), Chapter 5. In agreement with this regulation, the KKL Level 2 study was built on the Plant Damage States (PDS) obtained from the current KKL Level 1 PSA, which covers all hazards and all Plant Operating States (POS), i.e. power operation, low power and shutdown.

Regulatory guide ENSI-A05 and its contents outline were rigorously followed. A tabulation of the requirements showed that the KKL Level 2 PSA meets and in certain areas even exceeds ENSI-A05 requirements. Furthermore, international guides and standard such as IAEA SSG- 4 (Ref. 2), NUREG/CR-6595 (Ref. 3) and ASAMPSA2 (Ref. 4) were reviewed and applied, with priority and precedence however given to ENSI-A05 requirements.

I. DEFINITION AND QUANTIFICATION OF PLANT DAMAGE STATES

The KKL PSA model is a fully coupled three stage *RiskSpectrum* model. In this approach, the Level 1 PSA is used to determine the Core Damage States (CDS) and calculate the Core Damage Frequency (CDF). In a next stage, the linked Level 1+ addresses containment systems and related operator actions, including possible Severe Accident Management (SAM) measures that may mitigate the releases, for each CDS. Finally, the Level 2 addresses the phenomenological and physical events that can occur during and after core melt. For any accident scenario, the plant system status is transferred to the Level 2 model from Level 1+ via so-called Plant Damage States (PDS). Fig. 1 depicts the different PSA levels and how they are linked together.

It is important to mention that the KKL Level 2 exclusively models the 'physics' involved during severe accidents and is therefore highly independent of the Level 1 and Level 1+. All non-physical Severe Accident Management (SAM) measures are queried upstream in the Level 1+ and conveyed to Level 2 through the PDS.

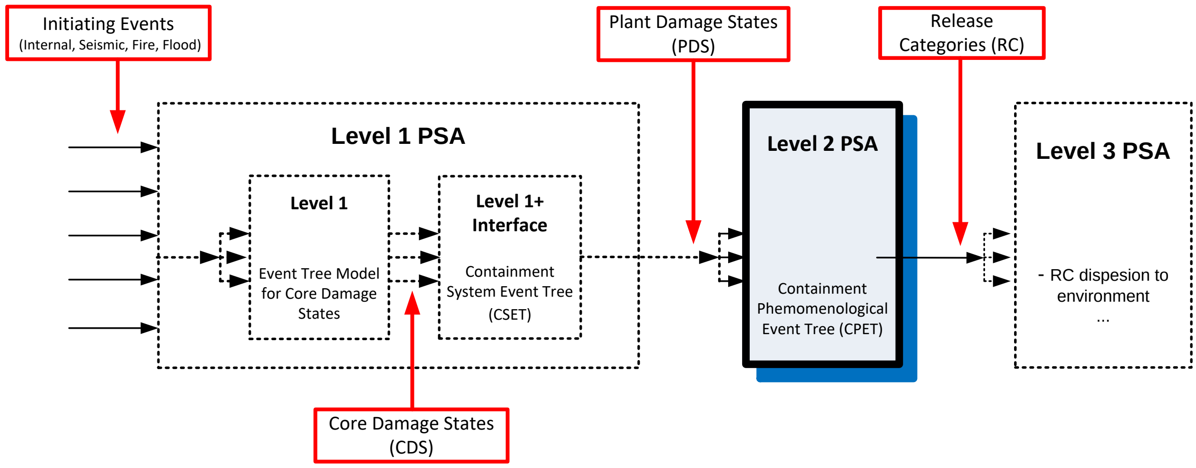


Fig. 1: Overview of the KKL PSA levels

PDS designators are used to characterize the plant status for Level 2 analysis of severe accident progression. A detailed multistate PDS matrix with a total of 2342 possible Plant Damage States was developed, depicting the containment status and the different containment system availabilities. The PDS matrix covers all 21 Plant Operating States (POS) defined in KKL operational Technical Specifications. They were subsequently grouped into one POS for power operation (incl. low power) and five POS for shutdown operation. For power operation, the PDS matrix distinguishes between states with successful control rod insertion (SCRAM) and Anticipated Transients Without Scrams (ATWS). In order to ensure full coupling between Level 1 and Level 1+, all core damage sequences of Level 1 are assigned to a PDS (no dead links). Out of all the possible PDS end states, there were in total 531 distinct PDSs with non-zero frequency.

Despite the fact that Swiss regulatory guideline ENSI-A05 allows for truncation of the 1% PDSs having the lowest frequencies, KKL deliberately decided to ignore this screening criterion. Instead, all PDS with zero frequency (i.e. without minimal cutsets above cutoff), were artificially assigned dummy low frequency in order to make them eligible for the subsequent binning process as described below. This approach leads to a substantially more comprehensive and complicated PDS ranking and binning process, for which a designated computer code had to be developed. Binning PDS into a lower number of Key Plant Damage States (KPDS) is necessary in order to make the analysis manageable.

The automatic ranking and binning technique is based on (i) PDS frequency and (ii) severity factors for each PDS designator. The severity factors are used to provide a numerical estimate of the severity of the accident consequences, based on weighting factors for each PDS designator. In the binning algorithm, similar PDS are first identified based on major containment characteristics. Next, the PDS with low frequencies and low severity are conservatively grouped with PDS with both higher frequencies and higher severity to form the KPDS, a technique known as PDS condensation. Special attention was put to Filtered Containment Venting System (FCVS) characterized by its large decontamination capability such that too conservative PDS condensation was prevented.

In order to ensure complete coupling between Level 1+ and Level 2, it is of crucial importance not to screen out any PDS during the KPDS binning process (this also applies to PDSs with zero frequency). This full-coupling is essential for LERF-based risk-informed analyses and for the well-known issues of “configuration control” between model revisions, as both specific unavailability configurations and/or changes in the model may have a huge impact on the PDS frequencies (e.g. initially zero-frequency PDS may see their frequency increases to non-negligible levels). Had these PDS not been assigned to any KPDS, then considerable frequency would have been lost.

The automatic binning process, followed by case-to-case manual refinement, resulted in 22 KPDS (16 with successful SCRAM and 6 ATWS states) for power operation and 11 KPDS for shutdown.

II. CONTAINMENT PROPERTIES

The KKL containment is a MARK III containment with reinforced concrete shield building consisting of a free-standing cylindrical steel structure with a spheroidal head. The diameter of the containment is 36.6 m with a total height of 62.7 m, with a free (air) volume of 36’183 m^3. The cylinder is anchored to the 3 m thick reinforced concrete base slab. Major penetrations include the equipment hatch and the personnel airlock.

In order to determine the containment response to accident conditions, a structural analysis of the containment and drywell has been performed. The analysis was subsequently refined by Finite Element Methods (FEM) calculations for dominant failure locations as requested by ENSI-A05 (Fig. 2). For the equipment hatch for instance, the analysis yielded a containment leak area of 100 mm^2 at a pressure of 3.75 bara, increasing to 9'000 mm^2 at 6.1 bara. At 6.13 bara the analysis predicted gross containment failure in the cylindrical portion of the containment shell (cylindrical hoop failure). The structural analyses are validated by the results of the Containment Integrated Leak Rate Test (ILRT) performed every 10 years at KKL.

The KKL containment has no containment sprays installed, but is equipped with a passive (406.6 mm, 16 inch) rupture disk that bursts at 3.1 bara and protects the containment from slow over-pressurization. The ruptured disk opens a path to FCVS filter tanks that can retain inorganic iodine (CsI) as well as organic iodine, the latter through reaction with sodium thiosulphate. Furthermore, H_2 management in KKL containment is achieved by 50 active igniters located at various elevations of the containment. The projected future installation of Passive Autocatalytic Recombiners (PARs) has not been considered in the study.

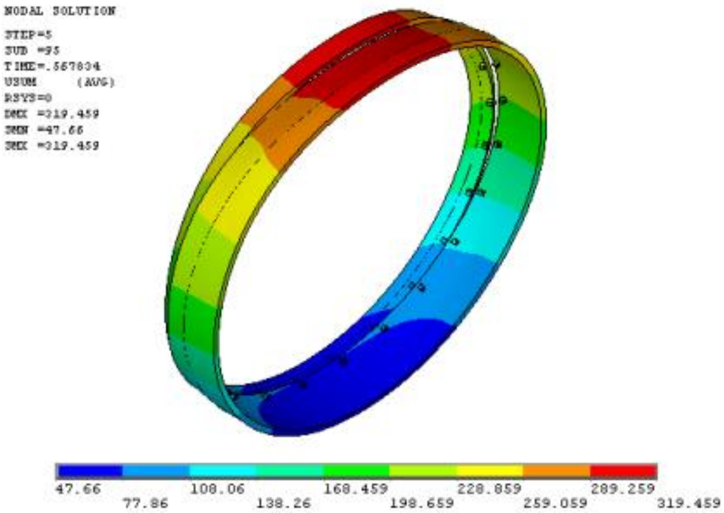


Fig. 2 Analysis of relative displacement of equipment hatch rings - isometric view

III. ACCIDENT SIMULATIONS WITH MELCOR CODE

The accident progressions of all 33 KPDSs have been simulated with severe accident code MELCOR version 1.8.6 (developed by Sandia National Laboratories). The code was integrated in the SIM Graphical User Interface (GUI) (MELSIM_KKL) developed by Risk Management Associates, Inc. (RMA), California. A view of the containment screen is shown in Fig. 3.

The development of the MELSIM_KKL started in 1996 and has been continuously expanded to improve the capabilities and fidelity in simulating the KKL behavior under accident conditions involving transients with and without core damage, with significant development steps conducted post-Fukushima. There now exist MELSIM_KKL models representing the reactor coolant system, the containment, the auxiliary building and all pertinent systems and controls to analyze accidents at full and low power, at shutdown conditions with the vessel head on, and at shutdown with the vessel head off. In addition, there is a model with all fuel relocated to the upper pools. Recent improvements/extensions include:

- Detailed containment nodalization to track the migration of H_2
- Calibration of the FCVS fission product scrubbing with the Sulzer test data for aerosol retention in the FCVS
- Modeling of the Vent Stack to account for possible H_2 burns
- Containment leakage behavior based on a new finite element analysis of the equipment hatch
- Modeling of off-site doses accounting for 3-dimensional diffusion, changing wind direction and speed and weather type (3-dimensional dispersion model for Level 2+ PSA)
- Upper Spent Fuel Pool model for refueling operations with part or all core relocated and stored
- Fuel Handling Building including the Lower Spent Fuel Pool (LSFP) model for fuel transfer analysis and resident assembly uncovery analysis. The LSFP model was excluded from Level 2 analysis though, as MELSIM_KKL transient testing predicted very long spent fuel uncovery periods
- Extension of radionuclide decay tables for shutdown accident simulations (up to 500h)
- Dynamic combustion conditions for deflagration, Flame Acceleration (FA) and detonation regimes based on NEA/CSNI/R(2000)7 criteria (Ref. 5).

The default MELCOR random ignitions at 8% (H_2/CO) concentration were suppressed based on recommendation of the Swiss regulator, as random burns would "passively" lower the effective H_2 concentration, preventing any identification of possible excursions into the detonative regime, hence masking important insights and leading to optimistic results.

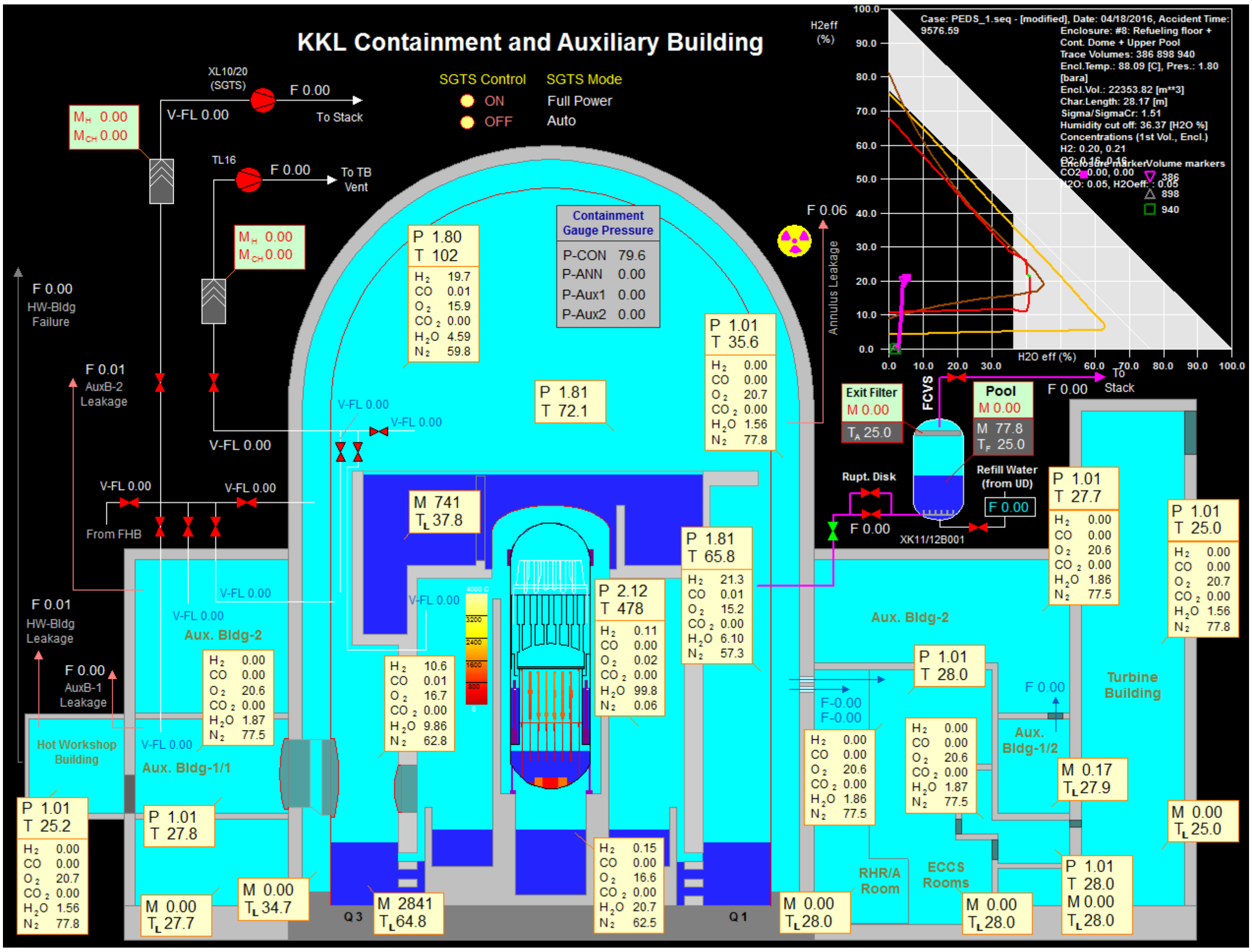


Fig. 3 Example of MELSIM_KKL user interface

In order to improve the data extraction process from MELSIM_KKL and its insertion into the PSA documentation, dedicated programs were developed at KKL. The scope covers extraction of relevant parameters (temperatures, water levels, reactor inventory loss flows, pressures, activities, etc.), combustion information, distribution of radionuclide classes in different control volumes, as well as accident logs. Fig. 4 and Fig. 5 show examples of how the final simulation data is presented.

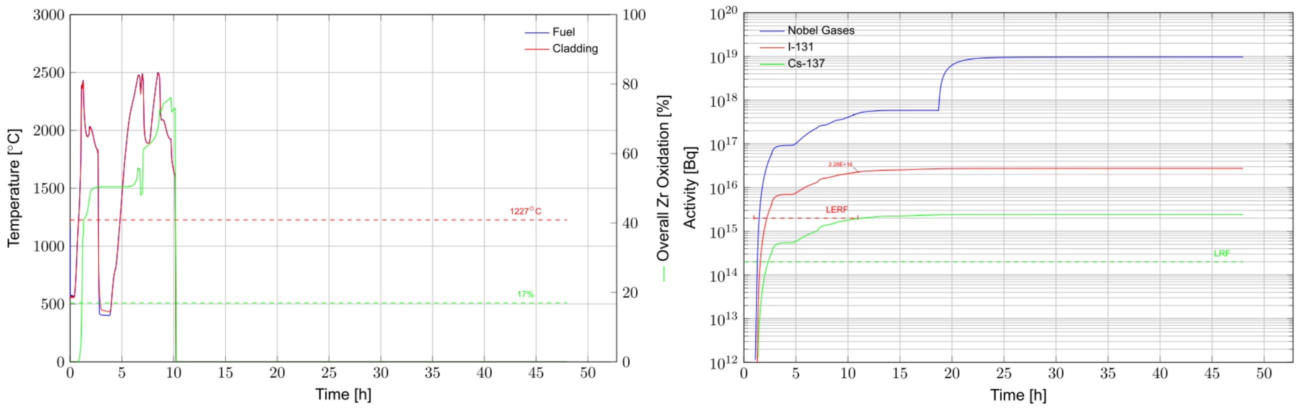
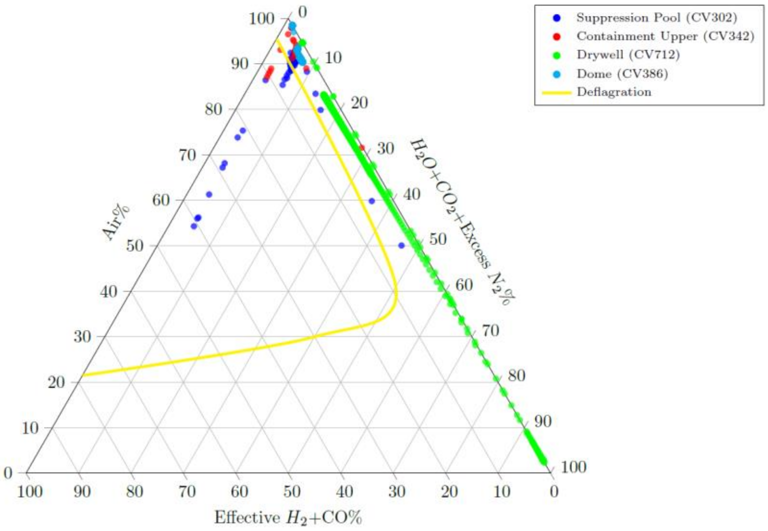
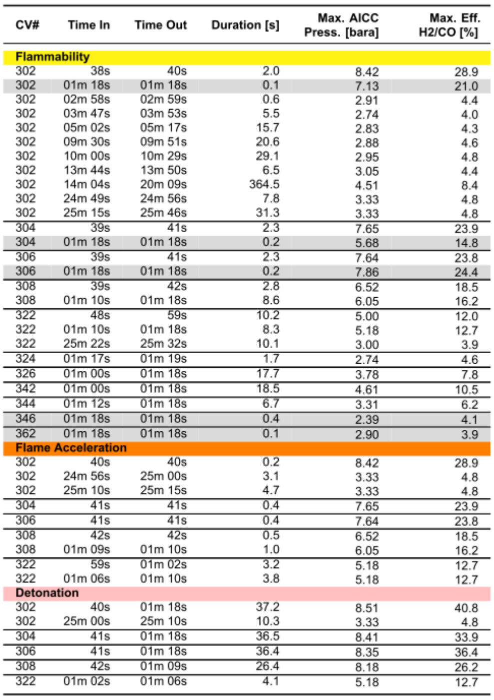


Fig. 4 Example of automated generation of plots from MELSIM_KKL parameters





CV#	Time In	Time Out	Duration [s]	Max. AICC Press. [bara]	Max. Eff. H2/CO [%]
Flammability					
302	38s	40s	2.0	8.42	28.9
302	01m 18s	01m 18s	0.1	7.13	21.0
302	02m 58s	02m 59s	0.6	2.91	4.4
302	03m 47s	03m 53s	5.5	2.74	4.0
302	05m 02s	05m 17s	15.7	2.83	4.3
302	09m 30s	09m 51s	20.6	2.88	4.6
302	10m 00s	10m 29s	29.1	2.95	4.8
302	13m 44s	13m 50s	6.5	3.05	4.4
302	14m 04s	20m 09s	364.5	4.51	8.4
302	24m 49s	24m 56s	7.8	3.33	4.8
302	25m 15s	25m 46s	31.3	3.33	4.8
304	39s	41s	2.3	7.65	23.9
304	01m 18s	01m 18s	0.2	5.68	14.8
306	39s	41s	2.3	7.64	23.8
306	01m 18s	01m 18s	0.2	7.86	24.4
308	39s	42s	2.8	6.52	18.5
308	01m 10s	01m 18s	8.6	6.05	16.2
322	48s	59s	10.2	5.00	12.0
322	01m 10s	01m 18s	8.3	5.18	12.7
322	25m 22s	25m 32s	10.1	3.00	3.9
324	01m 17s	01m 19s	1.7	2.74	4.6
326	01m 00s	01m 18s	17.7	3.78	7.8
342	01m 00s	01m 18s	18.5	4.61	10.5
344	01m 12s	01m 18s	6.7	3.31	6.2
346	01m 18s	01m 18s	0.4	2.39	4.1
362	01m 18s	01m 18s	0.1	2.90	3.9
Flame Acceleration					
302	40s	40s	0.2	8.42	28.9
302	24m 56s	25m 00s	3.1	3.33	4.8
302	25m 10s	25m 15s	4.7	3.33	4.8
304	41s	41s	0.4	7.65	23.9
306	41s	41s	0.4	7.64	23.8
308	42s	42s	0.5	6.52	18.5
308	01m 09s	01m 10s	1.0	6.05	16.2
322	59s	01m 02s	3.2	5.18	12.7
322	01m 06s	01m 10s	3.8	5.18	12.7
Detonation					
302	40s	01m 18s	37.2	8.51	40.8
302	25m 00s	25m 10s	10.3	3.33	4.8
304	41s	01m 18s	36.5	8.41	33.9
306	41s	01m 18s	36.4	8.35	36.4
308	42s	01m 09s	26.4	8.18	26.2
322	01m 02s	01m 06s	4.1	5.18	12.7

Fig. 5 Example of automated plot generation from MELSIM_KKL (combustion information). Grey rows represent real combustion events triggered by active igniters

The outcomes of the MELCOR simulations served as a basis for determining the split fractions, i.e. the failure probabilities of Containment Phenomenological Event Tree function events, as explained in following section.

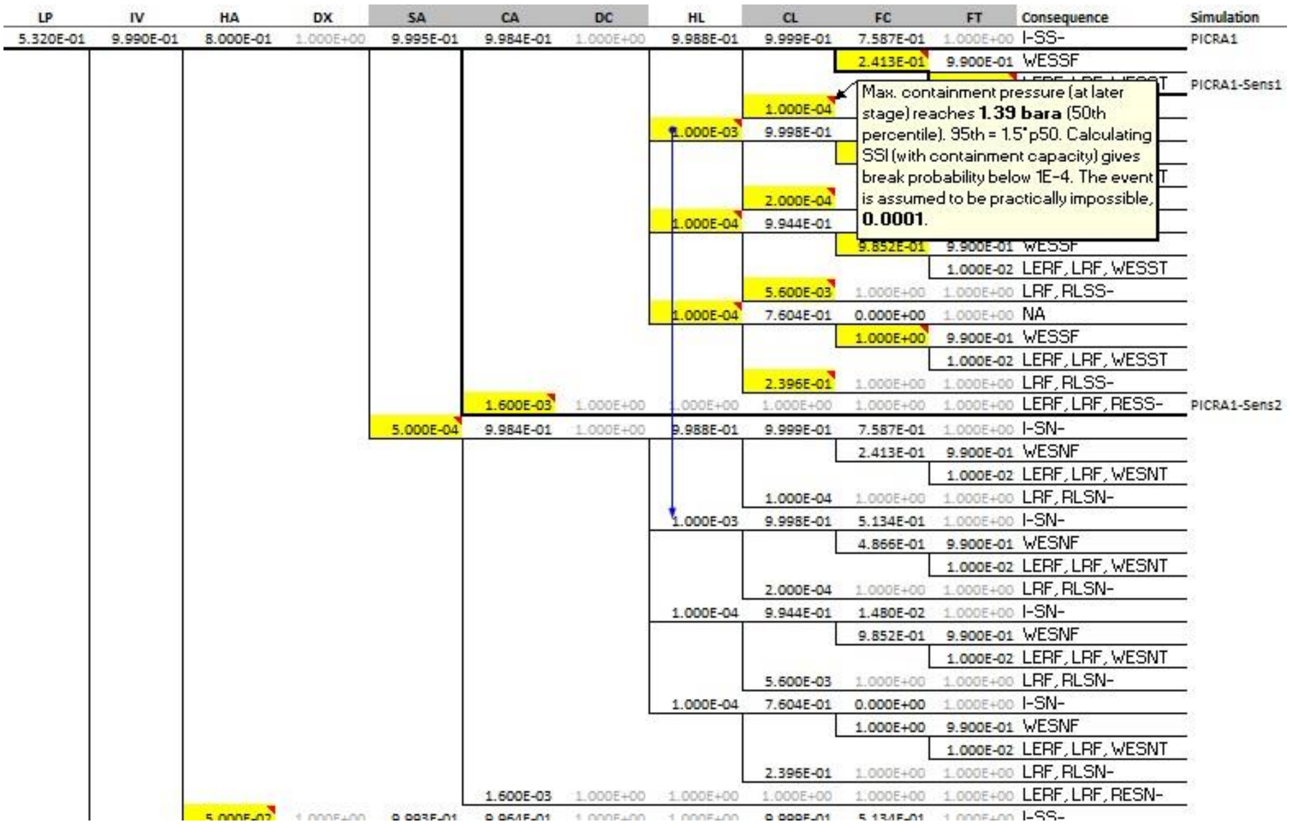
IV. SEVERE ACCIDENT PROGRESSION AND SOURCE TERM ANALYSIS

The accident progression for the KKL Level 2 analysis is modeled in a Containment Phenomenological Event Tree (CPET), assessing the likelihood of physical phenomena (using "split fractions") occurring in the containment (e.g. H_2 combustion) as well as the performance of containment systems (e.g. containment integrity, FCVS relief and filtering capability, H_2 igniters). The end states of the CPETs depict the different Release Categories (RC) characterized by their specific source terms, taking all possible release paths and retention phenomena into account.

Typically, split fractions are calculated using standard Stress Strength Interaction (SSI) analysis (interference integral) for pressure loads on containment shell, drywell, or inside FCVS tanks. For phenomena with large uncertainties like the impacts of ex-vessel steam explosion or H_2 detonation events, an expert judgment approach was applied.

In this study, a total of 36 Release Categories were defined, meeting the requirements of regulatory guideline ENSI-A05 on containment status (isolated, vented, ruptured, bypassed, etc.), time of release and scrubbing mechanisms. CPETs have been developed for each KPDS, in a first step in *MS-Excel* in order to provide effective visualization and reviewability, and a convenient interface for future integration into the PSA model (Fig. 6).

The *MS-Excel* approach was highly appreciated by the Swiss regulator, as it guarantees a clear identification of the effectively simulated sequences (bolded in Fig. 6), a direct visualization of CPET split fraction values, their justification and how they relate to other split fractions (indicated with blue arrows in Fig. 6). An additional benefit of this *MS-Excel* based approach lies in the direct generation of a standalone document report (generated using a Macro) for all CPETs. This includes the underlying split fraction justifications, identified by column and row label.

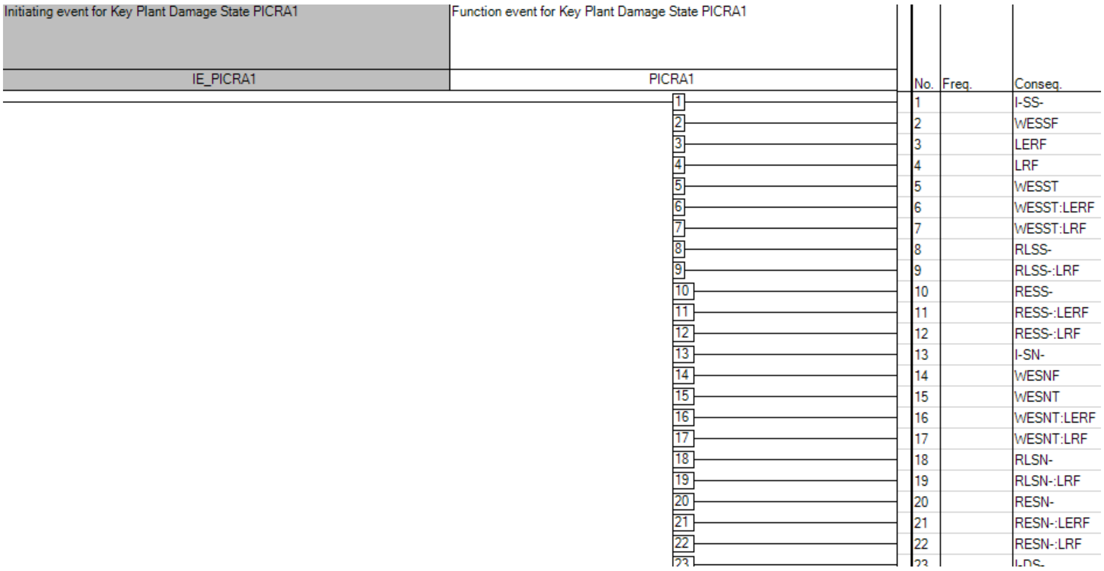


Max. containment pressure (at later stage) reaches **1.39 bara** (50th percentile). 95th = 1.5*p50. Calculating SSI (with containment capacity) gives break probability below 1E-4. The event is assumed to be practically impossible, **0.0001**.

Fig. 6 CPET as modelled in external *MS-Excel* application

Next, the event trees are processed by a dedicated computer code developed at KKL that automatically simplifies the CPET by combining the split fractions of sequences with same consequence into point-value fractional contribution (probability) for each consequence (see Fig. 7). The tool also creates all the necessary Basic Events (BE), representing the fractional contributions to each Release Category, as well as the Event Tree structure with proper consequences. Dedicated consequence codes (e.g. "WESST:LERF" or "WESST:LRF") are included in the simplified Event Tree, so that relative RC contributions to LERF/LRF can be readily quantified, as required by ENSI-A05 guideline. Note that the simplified approach is only possible because the CPET are independent from Level 1 and Level 1+, as all non-physical Severe Accident Management (SAM) measures (like operator actions and system dependencies) are queries upstream in Level 1+ and conveyed to Level 2 through PDS designators.

To summarize, the CPET Excel file serves as a single, integrated data source for CPET development, documentation and automated import of the CPET into the *RiskSpectrum* model. In addition, the approach provides a significant speed-up in LERF calculation, as the complexity of the Master Fault Tree developed by the *RiskSpectrum* engine (*RSAT*) is greatly reduced. In parallel, KKL sponsored the development of new *RSAT* functionalities by *RiskSpectrum* developers, to further improve calculation efficiency, for example by allowing input of a Consequence Analysis Case (CAC) as initiating event. Testing of the new features indeed resulted in additional speed-up of LERF quantification.



No.	Freq.	Conseq.
1		I-SS-
2		WESSF
3		LERF
4		LRF
5		WESST
6		WESST:LERF
7		WESST:LRF
8		RLSS-
9		RLSS-:LRF
10		RESS-
11		RESS-:LERF
12		RESS-:LRF
13		I-SN-
14		WESNF
15		WESNT
16		WESNT:LERF
17		WESNT:LRF
18		RLSN-
19		RLSN-:LRF
20		RESN-
21		RESN-:LERF
22		RESN-:LRF

Fig. 7 Simplified Level 2 Event Tree in *RiskSpectrum* software

V. RESULTS AND INSIGHTS

The main results of the KKL PSA Level 2 analysis, namely Large Early Release Frequency (LERF) and Large Release Frequency (LRF) are shown in Table I for Power and Shutdown domains (as indicative values).

TABLE I Results of KKL PSA Level 2

Power LERF	$7.0 \cdot 10^{-7}$ per year
Power LRF	$9.2 \cdot 10^{-7}$ per year
Shutdown LERF	$2.8 \cdot 10^{-7}$ per year
Shutdown LRF	$3.2 \cdot 10^{-7}$ per year

The Level 2 PSA analysis demonstrated the high mitigation effectiveness of the installed FCVS system and of proper H_2 management measures. It also helped to identify seismically vulnerable electrical cabinets with large LERF contribution (i.e. affecting both Safety Level 3 and 4 functions).

The following diagrams (Fig. 8 and Fig. 9) show indicative CDF and LERF distributions for both Power and Shutdown domains. As expected, the Power LERF contribution originates mainly from external events, as opposed to Shutdown domain where the Containment is already open in most POSs. As can be seen in Fig. 9, LERF is largely dominated by external initiating events (i.e. strong earthquakes) where operator actions are restricted and global damages expected.

The relatively large LERF to CDF ratio of KKL (~ 0.3) is partly explained by the Swiss definition of LERF which is defined as the expected number of events per calendar year with a release of more than $2 \cdot 10^{15}$ Bq of Iodine-131 within the first 10 hours after core damage. The definition of LERF is a matter of great controversy; in many countries, it is less conservatively defined as either 10 hours after the initiating event, or simply as a rough threshold for prompt fatalities, typically 10% of the core inventory of a large power reactor (Ref. 6).

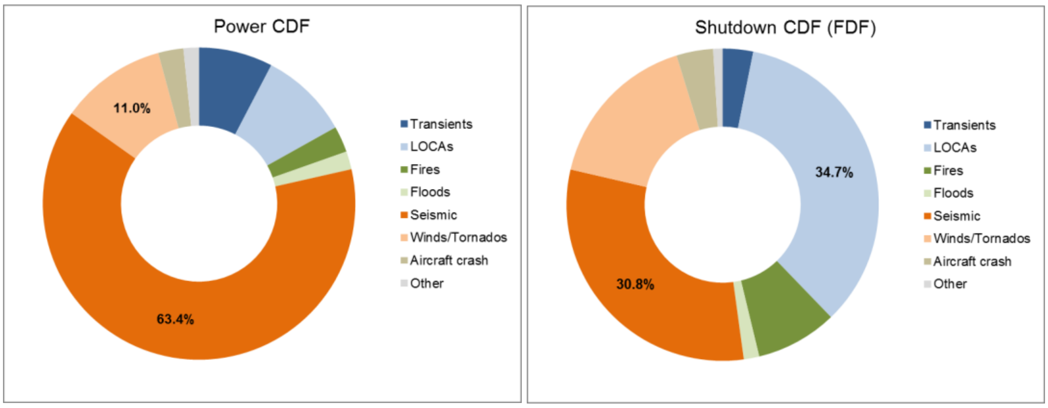


Fig. 8 CDF distribution for all events and hazards (Power and Shutdown)

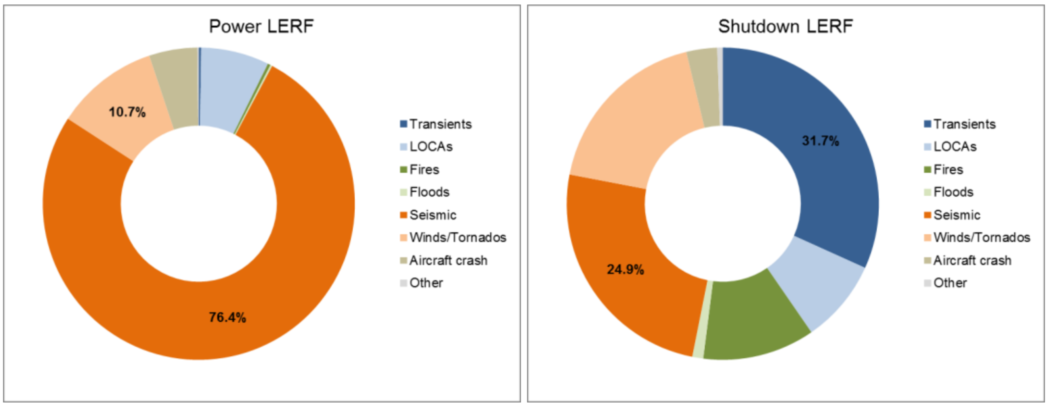


Fig. 9 LERF distribution for all events and hazards (Power and Shutdown)

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