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An approach to address probabilistic assumptions on the availability of safety systems for deterministic safety analysis

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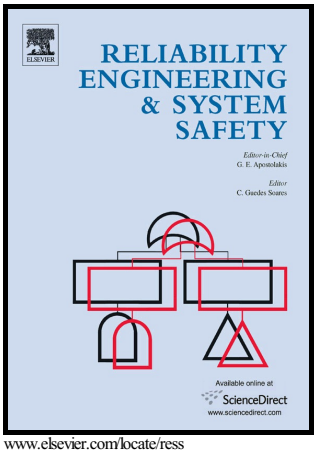

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An approach to address probabilistic assumptions on the availability of safety systems for deterministic safety analysis

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ABSTRACT
There is an attempt nowadays to provide a more comprehensive and realistic safety assessment of design and operation of Nuclear Power Plants. In this context, innovative approaches are being proposed for safety assessment of nuclear power plants design including both design basis conditions and design extension conditions. An area of research aims at developing methods for combining insights from probabilistic and deterministic safety analyses in Option 4, also called realistic approach, from the International Atomic Energy Agency specific safety guide. The development of Option 4 or realistic approach involves the adoption of best estimate computer codes, best estimate assumptions on systems availability and best estimate of initial and boundary conditions for the safety analysis. This paper focusses on providing the fundamentals and practical implementation of an approach to integrate PSA-based probabilistic models and data, which incorporate best estimate assumptions on the availability of safety systems, into Option 4. It is presented a practical approach to identify relevant, i.e. most probable, configurations of safety systems and to assess the associated occurrence probability of each configuration using PSA models and data of a NPP, which is based on the use of a Pure Monte Carlo method. An example of application is provided to demonstrate how this approach performs. The case study focusses on an accident scenario corresponding to the initiating event "Loss Of Feed Water (LOFW)" for a typical three-loops Pressurized Water Reactor (PWR) NPP.

Keywords
Extended BEPU, PSA, Option 4, realistic approach, probabilistic, deterministic, uncertainty, safety analysis, Best Estimate Plus Uncertainty methodology, design basis conditions, design extension conditions

LIST OF ACRONYMS

AFW Auxiliary Feedwater system
AS Accidental Sequence
BE_k Basic Event *k* belonging to the Boolean Equation (BE) of a TC_{ij}
BEAS Boolean Equation of AS
BEPU Best Estimate Plus Uncertainty methodology
$BESF_i$ Boolean Equation of SF_i
$BETC_{ij}$ Boolean Equation of TC_{ij}
CCF Common Cause Failure
CD Core Damage
CDF Core Damage Frequency
DBA Design Basis Accidents
DBC Design Basis Conditions
DEC Design Extension Conditions
DSA Deterministic Safety Analysis
EBEPU Extended BEPU methodology
ET Event Tree
FB Feed and Bleed
FOM Figure Of Merit
FOS First Order Statistics
FT Fault Tree
IAEA International Atomic Energy Agency
IE Initiating Event
IHI High Pressure Injection system – injection mode

IHR High Pressure Injection system – recirculation mode
LB Licensing Basis

LOFW Loss of Feed Water initiating event
MCS Minimal Cut Set
MSIV Main Steam Isolation Valve
NRC Nuclear Regulatory Commission
NPP Nuclear Power Plant
OS Order Statistics
PDF Probability Distribution Function
PMCM Pure Monte Carlo Method
PORV Pressure Operated Relief Valves
PRZ Pressurizer
PSA Probabilistic Safety Analysis
PWR Pressurized Water Reactor
RCS Reactor Coolant System
RPS Reactor Protection System
RV Relief Valve
SD Steam-Dump valve
SF_i Safety Function *i*
SG Steam Generator
STL Standard Tolerance Level
SV Safety Valve
TC_{ij} Train/Component *j* of Safety Function *i*
TH Thermal Hydraulic
TOPs Top Events

1 INTRODUCTION

Nuclear industry has relied on the concept of defense in depth and safety margins to deal with the uncertainties associated with the design and operation of nuclear facilities. In this context, both deterministic and probabilistic safety analyses are performed with an aim to achieve regulatory approval of Nuclear Power Plant (NPP) design and operation according to well-established licensing basis.

The adoption by regulators of the risk-informed decision-making philosophy [1] represents a key milestone to understand both the evolving regulatory framework and the growing research interest towards developing methods for using Probabilistic Safety Analysis (PSA) results into requirements and assumptions in Deterministic Safety Assessment (DSA) and vice versa. There is an attempt to provide a more comprehensive and realistic safety assessment of reactor design and operation. In addition, Fukushima Daiichi accident has raised new challenges such as the revision of current design license basis accounting for not only design basis conditions (DBC), e.g. anticipated occupational occurrences and design basis accidents (DBA), but also design extension conditions (DEC), e.g. DEC without and with fuel damage, in a context where innovative approaches of safety assessment of current NPP are welcome.

What concerns DSA (Deterministic Safety Analysis), the International Atomic Energy Agency (IAEA) produced guidance on the use of deterministic safety analysis for the design and licensing of nuclear power plants (NPPs): ‘‘Deterministic Safety Analysis for Nuclear Power Plants Specific Safety Guide,’’ Specific

Safety Guide No. SSG-2 [2], which is now under revision [3]. SSG- 2 addresses four options for the application of DSA.

Options 1 and 2 are conservative and they have been used since the early days of civil nuclear power, and are still widely used today. However, the desire to utilize current understanding of important phenomena and the availability of reliable tools for more realistic safety analysis without compromising plant safety has led many countries to use option 3. Option 3 involves the use of best-estimate codes and data together with an evaluation of the uncertainties, the so called BEPU (Best Estimate Plus Uncertainty) methodology. Several BEPU approaches have been developed [4-11], some of them in scopes that are accepted by the regulator authorities nowadays. Most of them are based on propagation of input uncertainties and make use of the Wilks'–based methods to determine the number of calculations of the output (usually safety-related parameters) needed to verify compliance of acceptance criteria with "Standard Tolerance Levels (STL)" (typically 95/95) in accordance with current regulatory practice. Ref. [4] provided a review of groups of tools and methods being proposed up to 2008 to perform BEPU analysis, e.g. statistical methods, use of surrogate models, etc. Pourgol-Mohammad, 2009 [5] and D'Auria et al., 2012 [6] published the fundamentals of several of them. Wilsom, 2013 [7] presented historical insights in the development of BEPU safety analysis. Unal et al., 2011 [8] proposed an improved BEPU methodology including advanced validation concepts to license evolving nuclear reactors and more recently Queral et al., 2015 [9] presents an application of the BEPU methodology for the safety analysis of a Large-Break LOCA with TRACE code of an advanced NPP.

Development of Option 4 of the IAEA Specific Safety Guide SSG-2 [2, 3], which is also called realistic deterministic safety analysis, is currently under research. An area of research in this context aims at developing methods for combining insights from probabilistic and deterministic safety analyses [12, 13]. Even more, some research aims at developing methods for integrating deterministic and probabilistic safety assessment or even at developing an integrated safety assessment methodology [14-16]. The new methods, such as the one presented in [13], are intended to be used for safety assessment of some current NPP design basis conditions, e.g. anticipated occupational occurrences also called DBC-2, and design extension conditions without and with significant fuel degradation, which are also called DEC-A and DEC-B accidents respectively. Option 4 is not allowed for design basis accidents (DBA) within the design basis conditions, called DBC-3 and DBC-4, where it is proposed only the adoption of Options 1 to 3 (see section 2.15 in Ref. [3]).

In this research context, it is proposed to face the challenge of combining the use of well stablished BEPU methods and probabilistic-based assumptions on systems availability to build an extended BEPU methodology, called EBEPU methodology [12, 13], following the fundamentals of Option 4 based on the IAEA SSG-2 guide, which can be used for realistic deterministic safety analysis of current NPP designs [2, 3]. In Ref. [13], a novel EBEPU approach was introduced merging traditional BEPU methods and PSA-based assumptions on the availability of safety systems, which consists of the following steps:

1. Selection of the accident scenario.
2. Selection of the safety criteria linked to the accident scenario under study and the FOMs (Figures of Merit) involved in the acceptance criteria.
3. Identification and ranking of relevant physical phenomena based on the safety criteria.
4. Selection of the appropriate TH (Thermal Hydraulic) parameters to represent those phenomena.
5. Identification of relevant safety-related systems involved in the accident scenario.
6. Selection of relevant components/trains of the above redundant safety systems that are responsible for performing the intended safety function to mitigate accident consequences.
7. Development of the TH computer model of the accident scenario, e.g. develop an input for TRACE code [17].
8. Association of PDF (Probability Density Functions) for each selected TH parameter.
9. Identification of relevant, i.e. most probable, system configurations based on the availability of safety components/trains and association of a probability of occurrence for each configuration.
10. Random sampling of the selected TH parameters and plant configurations. Sample size (N) will depend on the particular statistical method and the acceptance criterion adopted to verify compliance of safety criteria. Perform N computer runs to obtain FOMs for each run.
11. Processing the results of the multiple computer runs (N) to estimate either the probability distribution of the FOMs, or rather some descriptor of this distribution, such as for example a percentile of the FOM, or a tolerance level of each FOM with STL using OS, e.g. the FOS.
12. Verify compliance of acceptance criterion for each FOM

The main difference between a typical BEPU and this EBEPU approach is the incorporation of steps 6 and 9 to account for best estimate assumptions, i.e. PSA-based assumptions herein, on safety systems availability under the EBEPU approach. In addition, step 10 must be updated to account also for random sampling of safety systems configurations in addition to TH parameters. At last but not at least, the TH computer model must be developed in step 7 with appropriate level of detail at component/train in a coherent manner with step 6 in order to make it possible to address the particular configuration of the safety systems required for each TH simulation or computer run in step 10. BEPU approaches focuses only on an enveloping sequence representing a conservative progression of the accident scenario (step 1) departing from an initiating event. Thus, for such an enveloping accidental sequence, it is adopted a conservative assumption on the availability of safety systems (steps 5 and 7), so that steps 6 and 9 are not necessary. In Ref. [18], a comparison between traditional BEPU and Extended-BEPU approaches for Deterministic Safety Analysis is presented.

This paper presents a practical approach to identify relevant configurations of safety systems and to assess the associated occurrence probability of such configurations using PSA results of a NPP, i.e. how to develop step 9 in the above EBEPU approach. The most relevant configurations mean the most probable ones according to

PSA-based probabilistic models and data, which incorporate best estimate assumptions on the availability of safety systems. An example of application is provided to demonstrate how this approach performs. The case study focusses on an accident scenario corresponding to the initiating event "Loss Of Feed Water (LOFW)" for a typical three-loops Pressurized Water Reactor (PWR) NPP.

2 METHODOLOGY

Figure 1 provides an outline of the procedure proposed to identify a list of relevant sets of configurations of Trains/Components (TC) of safety systems (available/unavailable TC) and to assess the associated occurrence probability for each set of TC configurations using PSA models and data for a NPP. Each step of the proposed approach is explained next.

Figure 1. Approach to identify and associate probabilities for safety systems configurations

Step 1: Identification of the PSA-based initiating event, accident scenarios and safety functions.
The procedure starts with the adoption of the Initiating Event (IE) and corresponding event tree (ET) available from the PSA of the NPP under study, which is normally implemented in a PSA computer software, e.g. Risk Spectrum software [19]. The procedure will then focus on the whole set of accident scenarios departing from the IE. Each Accident Scenario (AS) represents an accidental sequence belonging to the event tree, which involves the simultaneous occurrence of the initiating event and either success or failure (depending on the particular sequence) of the *i* safety functions SF_i taking part of this accidental sequence AS. Herein, the whole set of SF_i taking part of the PSA-based ET is considered. This information is available from the PSA of the NPP under study and implemented in a PSA computer software.

Step 2: Identification of trains and components and set configurations template $\boldsymbol{x}=\{TC_{ij}\}$
Each safety function SF_i in turn is developed by a number *j* of relevant trains/components TC_{ij}. Then, the SF_i must be split into functional TC_{ij} depending on the particular configuration of the safety system responsible for performing the safety function SF_i, for example, attending to the diversity and redundancy of trains/components performing the safety function. The procedure is repeated for each SF_i in order to build up a generic set of configurations of Trains/Components $\boldsymbol{x}=\{TC_{ij}\}$. Note dimension and configuration of vector $\boldsymbol{x}$, *e.g.* $\boldsymbol{x}=\{TC_{11}, TC_{12}, TC_{21}, TC_{22}, TC_{23}\}$, depend on the number of safety functions and corresponding number of trains/components that take part of the particular accident scenario, i.e. AS, studied.

Step 3: Formulate Boolean equation for each TC, i.e. $BETC_{ij}=h\{BE_k\}$
Next, each TC_{ij} must be associated a Boolean equation, i.e. $BETC_{ij} = h\,(BE_k)$, which must represent the condition of availability of the TC_{ij}. Then, its complementary Boolean equation, $\overline{BETC_{ij}}$, will represent the condition of unavailability of the TC_{ij} .

Figure 2 outlines the key relationships between the formulation of $BETC_{ij}$ and the logical models and data taken from the PSA. Boolean equation $\overline{BETC_{ij}} = function$ (TOPs) is the Boolean equation representing the condition of unavailability of *j* train/component of the *i* safety function, which can be derived by using the corresponding Fault Trees (FT) within the PSA modeling available and the PSA software. Normally, one can use FT already developed that corresponds to intermediate TOP events (TOPs) already available from the PSA study, which consist of logic relationships of *k* basic events, BE_k, representing each BE_k a basic unavailability contribution, for example a component failure, a human error, a maintenance activity, etc., taking part of the TC_{ij} belonging SF_i. Note, each BE_k is associated a probability distribution function (PDF), which is taken directly from PSA data implemented in the PSA software, which are already available from the PSA study. For sake of usefulness in developing the next steps of the approach, instead of using the FT directly, the $BETC_{ij}$ are formulated in terms of Minimal Cut Sets (MCS), $\overline{BETC_{ij}} = MCS(BE_k)$, as it is usual in PSA logical modeling and quantification.

Figure 2. Approach to obtain Boolean equations of TC_{ij}

In summary, standard PSA models and data available for the IE under study provide PDFs for BE_k events of interests. In turn, BE_k events and their corresponding PDFs are used to formulate Boolean equations $BETC_{ij}$ = MCS (BE_k) that are derived in terms of minimal cut sets using the PSA software. The MCS for each $BETC_{ij}$, the basic events BE_k and their corresponding PDFs can be exported from the PSA software and they can be imported to built the corresponding equivalent Boolean Equations and probabilistic data as spreadsheets in Microsoft Excel with add on @Risk 7 (Palisade Decision Tools) [20].

Step 4: Evaluate each $BETC_{ij}$ to conclude TCij is available or not

Next, these Boolean equations and PDFs implemented as spreadsheets are used to obtain a list of relevant configurations of safety systems (available/unavailable) and to assess the occurrence probability of each configuration developing the following steps. Note that herein relevant configurations of safety systems means the most probable configurations since a Pure Monte Carlo Method (PMCM) is used to look for them directly using the @Risk software.

First, each BE_k event is evaluated to occur (true) or not (false) by random sampling using its PDF and PMCM. Then, the resulting states of the BE_k (true or false) are propagated using the corresponding Boolean equations MCS(BE_k) to evaluate whether the trains/components TC_{ij} results in a state condition available ($BETC_{ij}$ = true) or unavailable ($BETC_{ij}$ = false). This provides a particular realization of the generic set of configurations of Trains/Components $\boldsymbol{x}$={TC_{ij}}. Thus, if $BETC_{ij}$ = "true" the corresponding TC_{ij} is replaced by a "1" in the generic set $\boldsymbol{x}$ or by a "0" otherwise. Each realization of the set, for example x_n = {1,1,0,0,1,

….}, represents a probabilistic/realistic configuration of safety systems given by the particular values taken by all TC_{ij} associated to the SF_i under study.

Step 5: Update list ***x*** of configurations. Sample size is representative?

The above procedure is then repeated in order to obtain and update a list of safety system configurations, which is either increased with a new configuration or updated with a new occurrence of an existing one after every sampling. The sample size has to be adjusted as necessary, since the procedure must end once the list is representative of the most probable safety system configurations, i.e. there is enough diversity and repetitions of the most probable configurations. A criterion to stop the search may be based on the comparison of the probabilities of the most a less probable configurations found, e.g. when they are separated by several orders of magnitude. Another criterion may be that the configurations found represents a cumulative probability of occurrence of configurations high, such as for example 0,98 or higher.

Step 6: Estimate Probability of configurations, P(***x***)

Based on the repetition of the above procedure using a PMCM, it is possible to estimate the probability of occurrence of each configuration x_n found, i.e. $P(x_n)$, based on the fraction between the number of times each configuration appears and the sample size.

Step 7: Grouping of equivalent configurations and built a list of ***g*** groups

Next, the list of safety system configurations is post-processed. The objective is grouping configurations that are equivalent to each other to build just one group for each set of equivalent configurations. For example, imagine a safety function consisting of three redundant trains. Thus, those configurations including the failure of only one of the trains would belong to the same group. In addition, those configurations including the failure of two trains would belong to another group, and so on. This way, it is possible to build a list of equivalent groups, ***g***, departing from the derived set of system configurations, ***x***.

Step 8: Estimate probability of groups P(***g***)

In addition, it is possible to obtain the probability of a realization of the configuration represented by each group, $P(g_m)$, adding the probability $P(x_n)$ of just those $x_n \in g_m$.

Step 9: Verify probabilities using original PSA results

Last, in order to verify the consistency of the results found, the above Boolean equations $BETC_{ij}$ implemented as spreadsheets in Microsoft Excel with add on @Risk must be used to formulate Boolean equations of the form $BESF_i = g(BETC_{ij})$ in the same software to derive the logical representation of the condition of availability of each individual safety function SF_i in terms of the MCS of BE_k. This Boolean equation must be equivalent to the logical model built in the original PSA to represent the condition of availability of the safety function SF_i. Next, these Boolean equations $BESF_i$ must be used to formulate Boolean equations representing each

one the occurrence of the different accident scenarios, which are of the form BEAS = f ($BESF_i$). Again, one must verify the results found in this way are coherent with the results derived from the original PSA quantification.

3 CASE STUDY

3.1 *Description of the PSA-based initiating event and the corresponding event tree (Step 1)*

The case study focusses on an accident scenario corresponding to the initiating event "Loss Of Feed Water" for a typical three-loops Pressurized Water Reactor NPP. The group LOFW includes those transients involving total loss of main feed water to steam generators (SG), which reduce water level of SG and consequently reduce their capacity to extract heat from the reactor coolant system (RCS). In particular, this group includes initiating events of category 16 and 24 in EPRI/NP-2230 [21]. Figure 3 shows a typical event tree for the LOFW transient taken from the level 1 PSA available and the corresponding safety functions required following the occurrence of LOFW.

Figure 3 shows two alternative ways to remove heat from the RCS once the Reactor Protection System (RPS) is successful to shut down the NPP. One way involves the injection of water to SG by the Auxiliary Feed Water System (AFW) and evacuation of heat through steam-dump valves (SD), relief valves (RV) or safety valves (SV). Eventually, in case of RCS pressurization, there may be a need to reduce pressure by means of the PORV valves (and safety valves SV when required) of the pressurizer (PRZ). Second alternative involves removing heat from the RCS by means of "Feed and Bleed" function, i.e. extracting warm water opening PORV valves manually and injecting cold water using the high-pressure injection system (IHI). In addition, it is needed re-circulation of water from the RCS using the same system under recirculation operational mode (IHR) in order to keep a safe operational state of the NPP in the long term.

3.2 *Identification of Safety Functions and selection of relevant Trains/Components (Step 1)*

Each header of the event tree shown in the Figure 3 is related to a safety function in Table 1, which provides information on each header and the corresponding safety function name (SF_i), its success criteria involving the Trains/Components of the safety systems performing the safety function and its relevant TC_{ij} functions.

Figure 3. Event Tree for the LOFW transient

Table 1. Safety functions and success criteria required for LOFW. Relevant trains/components functions.

3.3 *Set up a template of safety systems configurations, x={TC_{ij}} (Step 2)*

Next step consists of building the vector representing a generic set of configurations of availability/unavailability of the relevant Trains/Components, i.e. $\boldsymbol{x}$={TC_{ij}}. In this example it is quite simple to set up this vector by using the information provided in the last column in Table 1 as follows:

$\boldsymbol{x}$ = {K, AFW1, AFW2, AFW3, PORV1o, PORV2o, SV1o, SV2o, SV3o, PORV1c, PORV2c, SV1c, SV2c, SV3c, SD1c, SD2c, SD3c, SD4c, SD5c, SD6c, SD7c, SD8c, MSIV1c, MSIV2c, MSIV3c, IHI1, IHI2, IHI3, PORV1mo, PORV2mo, FBIHI1, FBIHI2, FBIHI3, IHR1, IHR2, IHR3}

Vector $\boldsymbol{x}$ encodes a generic configuration of the availability of the safety systems. One realization of vector $\boldsymbol{x}$ will represent a particular configuration. The above vector contains 29 variables, TC_{ij}, where each one can take a value either "1" to represent the corresponding TC_{ij} is in a condition available or "0" otherwise (not available). Thus, based on the dimension of vector $\boldsymbol{x}$, there are 2^{29} combinations feasible (more than 500 million combinations). So that, enumeration of all of them is impracticable and one must look forward to finding at least the most relevant ones.

3.4 *Formulation of the Boolean equation for TC_{ij} in terms of PSA-based top and basic events (Steps 3 and 4)*

Next step involves the development of the Boolean equations to represent the condition of availability of the relevant TC_{ij}. Table 2 shows intermediate TOP events considered to formulate the corresponding Boolean equation for each TC_{ij} based on the PSA-based logic models available.

Table 2. TOP events and basic events related to safety trains and components.

For example, the Boolean equation representing the condition of availability of the first of three redundant trains of the AFWS can be formulated based on the information provided in Table 2 as follows:

$$\text{BEAFW1} = 1 - \overline{\text{BEAFW1}} = 1 - \text{GAFW001} \quad (1)$$

where, GAFW001 is the PSA-based TOP event representing the unavailability of the AFWS train 1 taken from the PSA available (see Figure 4). Boolean equations for the other two trains are similar. For sake of usefulness this top event is formulated in terms of MCS consisting of BE_k taking part of the top event as usual in PSA logical modeling and quantification (see Table 3). In addition, each basic event BE_k is associated a PDF, which is taken from PSA original data (see Table 4).

Figure 4. GAFW001 top event representing unavailability of the first of three redundant AFWS trains

Table 3. MCS corresponding to GAFW001 in terms of basic events.

Table 4. PDF of basic events BE_k of GAFW001 form original PSA data.

Another example, the Boolean equations representing the condition of availability of one train of the safety function corresponding to "primary pressure relief opens" can be formulated for the first PORV train and for the first SV train respectively as follows:

$$BEPORV1o = 1 - \overline{BEPORV1o} = 1 - \left[GPORV025 + GPORV007 + 1HFSPORVM \right] \quad (2)$$

$$BESV1o = 1 - \overline{BESV1o} = 1 - \left[GSV010 + GPORV005 \right] \quad (3)$$

where, GPORV025 and GPORV007 are PSA-based intermediate TOP events representing independent and common cause failures to open respectively of the first PORV1o train, while 1HFSPORVM is a basic event that represents the unavailability of the PORV1o to open due to maintenance activities. On the other hand, GSV010 and GPORV005 are intermediate TOP events representing independent and common cause failures to open respectively of the first SV1o train.

Last example, which is a little bit more complex, the Boolean equations representing the condition of availability of one train of the safety function corresponding to "primary pressure relief close" can be formulated for the first PORV train and for the first SV train respectively as follows:

$$BEPORV1c = 1 - \overline{BEPORV1c} = 1 - GPORV085 \quad (4)$$

$$SV1c = 1 - \overline{SV1c} = 1 - GSV150 * \left[(GPORV025 * GPORV026) + GPORV007 + 1HFSPORVM \right] \quad (5)$$

where, GPORV085 is an intermediate TOP event representing independent failure to close the first PORV1c train. On the other hand, GSV150 is an intermediate TOP event representing independent failure to close the first SV1c train. Note, this failure is applicable only if SV1o opens, which depends on the fact that both PORV1o and PORV2o fail to open.

Boolean equations representing the condition of availability of the remaining TC_{ij} trains/components included in vector $\boldsymbol{x}$ can be formulated in a similar way based on the information provided in Table 2 and PSA models and data.

3.5 *Identification of relevant safety systems configurations and probabilities, **x** and P(**x**) (Steps 5 and 6)*

The Boolean equations and data presented in the previous sections are used to develop the procedure proposed in Section 2. This procedure allows the identification of the relevant (the most probable) configurations of safety systems, i.e. relevant combinations of success and failures of safety trains/components, and at the same time it allows the estimation of a given probability of occurrence for each configuration.

These models in terms of minimal cut sets and data have been built as spreadsheets in Microsoft Excel with add on @Risk 6 (Palisade Decision Tools) [20]. The identification of configurations has been performed randomly by evaluating the Boolean equations based on Pure Monte Carlo sampling of the occurrence of basic events using their PDFs. The sample size has been adjusted manually to obtain a list of configurations that results representative as it includes enough diversity and repetitions of configurations, x_m. and at the same time the cumulative probability is very close to one.

Based on the final list of valid configurations found and the number of realizations of each configuration it is possible to estimate the probability of each configuration, P(x_m), given approximately by the frequency of occurrence of each configuration as compared to the sample size. The results are presented in the following.

Table 5 shows only the 32 most relevant configurations out of the 3000 found of the about 500 million configurations possible based on enumeration of combinations of the 29 variables in vector ***x***. The most relevant configurations represent a cumulative probability of 0,9837. In Table 5, every configuration is represented by a set of "1" and "0" values, each for the corresponding TC_{ij} safety train/component encoded in vector ***x***. A value "1" means the TC_{ij}, e.g. PORV1o, is available while a value "0" means it is unavailable.

Table 5. List of Safety Systems configurations, x_n, and corresponding probabilities, P(x_n).

3.6 *Grouping of equivalent configurations and probabilities, **g** and P(**g**) (Steps 7 and 8)*

Now, the list of safety system configurations found in previous section is post-processed. The objective is grouping configurations that are equivalent to each other to build just one group for each set of equivalent configurations. For example, imagine a safety function consisting of three redundant trains. Thus, those configurations including the failure of only one of the trains would belong to the same group. In addition, those configurations including the failure of two trains would belong to another group, and so on.

First step consists of building the vector representing a generic group of equivalent configurations of availability/unavailability of the relevant Trains/Components, i.e. ***g***. In this example, it is quite simple to set up this vector departing from vector ***x*** as follows:

g = {K, AFWS, PORVo, SVo, PORVc, SVc, SDc, MSIVc, IHI, FBIHI, PORVmo, IHR}

Vector $\boldsymbol{g}$ encodes a generic group of equivalent configurations of the availability of the safety systems. One realization of vector $\boldsymbol{g}$ will represent a particular group. The above vector contains 12 variables, TC_{ij}, where each one can take a value ranging in the interval given in the corresponding component of the equivalent vector {0-1, 0-3, 0-2, 0-3, 0-2, 0-3, 0-8, 0-3, 0-3, 0-3, 0-2, 0-3}.

This way, it is possible to obtain the list of equivalent groups, $\boldsymbol{g}$, departing from the derived set of system configurations, $\boldsymbol{x}$, in the previous section. In addition, it is possible to obtain the probability of a realization of the configuration represented by each group, $P(g_m)$, adding the probability $P(x_n)$ of just those $x_n \in g_m$.

Table 6 shows only the 16 most relevant groups of equivalent configurations out of the 507 groups, departing from 3000 configurations found of about 500 million configurations possible based on enumeration of combinations of the 29 variables in vector $\boldsymbol{x}$. The most relevant groups of configurations represent a cumulative probability of 0,9905. In Table 6, every configuration is represented by a set of numbers ranging each one between 0 and MAX, where MAX represents the maximum number of train/component redundancies.

Table 6. List of groups of equivalent configurations of safety systems, x_n, and probabilities, $P(x_n)$.

Figure 5 plots the probability of the groups of equivalent configurations found and their relationship with the accident sequence, AS, based on Figure 3. In Figure 5 most of the groups of equivalent configurations found belong to AS #1 as expected. For example, note that only 100 groups of 507 verifies that their probability $P(g_m) > 10^{-5}$, as one can realize looking at the left hand side in Figure 5, which correspond to accident scenarios belonging to AS #1 mainly, AS #2 and AS #3. In addition, note those AS ending with consequence core damage, CD, rank in the last positions of this Figure 5 (right hand side), which is coherent with PSA quantification results since CD may occur with very low probability once the LOFW initiating event occurs. The same happens for the AS corresponding to the ATWS.

Figure 5. Plot of probabilities of groups of configurations and AS to which they belong (see Figure 3 also)

4 CONCLUDING REMARKS

In this paper, it is proposed an approach that can be used to integrate probabilistic assumptions on the availability of safety system configurations into deterministic safety analysis of extensions to NPP design condi-

tions based on Option 4 of the IAEA SSG-2 guide, which will require combining the use of well stablished deterministic BEPU methods and realistic assumptions on availability of safety systems.

In particular, this paper proposes and demonstrate the performance of an approach to address PSA-based assumptions on the availability of safety systems, which allows finding realistic configurations on safety systems availability. The results of this preliminary case study demonstrate that the approach not only performs well but also it requires an important effort to adapt event trees, fault trees and probabilistic models and data available from the PSA.

Direct search of the most probable configurations based on Pure Monte Carlo sampling is the method used in this paper, which is just an option that performs in an affordable way for the case study. Note a method based on the enumeration of the whole set of feasible configurations and calculation of their corresponding probability is an unaffordable option based on the dimension of vector $\boldsymbol{x}$. Thus, 507 groups of equivalent configurations corresponding to a total of 3000 configurations of safety systems have been found of about 500 million configurations possible based on enumeration of combinations of the 29 variables in vector $\boldsymbol{x}$.

For example, note that only 100 groups of 507 verifies that their probability $P(g_m) > 10^{-5}$, which correspond to accident scenarios belonging to AS #1 mainly, AS #2 and AS #3. Those AS ending with consequence core damage, CD, rank in the last positions, which is coherent with PSA quantification results since CD may occur with very low probability once the LOFW initiating event occurs. In addition, notice also that AS ending with consequence CD are not of interest for DSA.

Last, notice that it would be possible to increase the number of configurations and groups found by increasing the sample size with the direct search procedure adopting Pure Monte Carlo sampling. However, future work should pursue the development of new and more efficient searching algorithms to find out the highest number of configurations possible with the lowest computational cost, since the computational effort required for large sample sizes increases exponentially.

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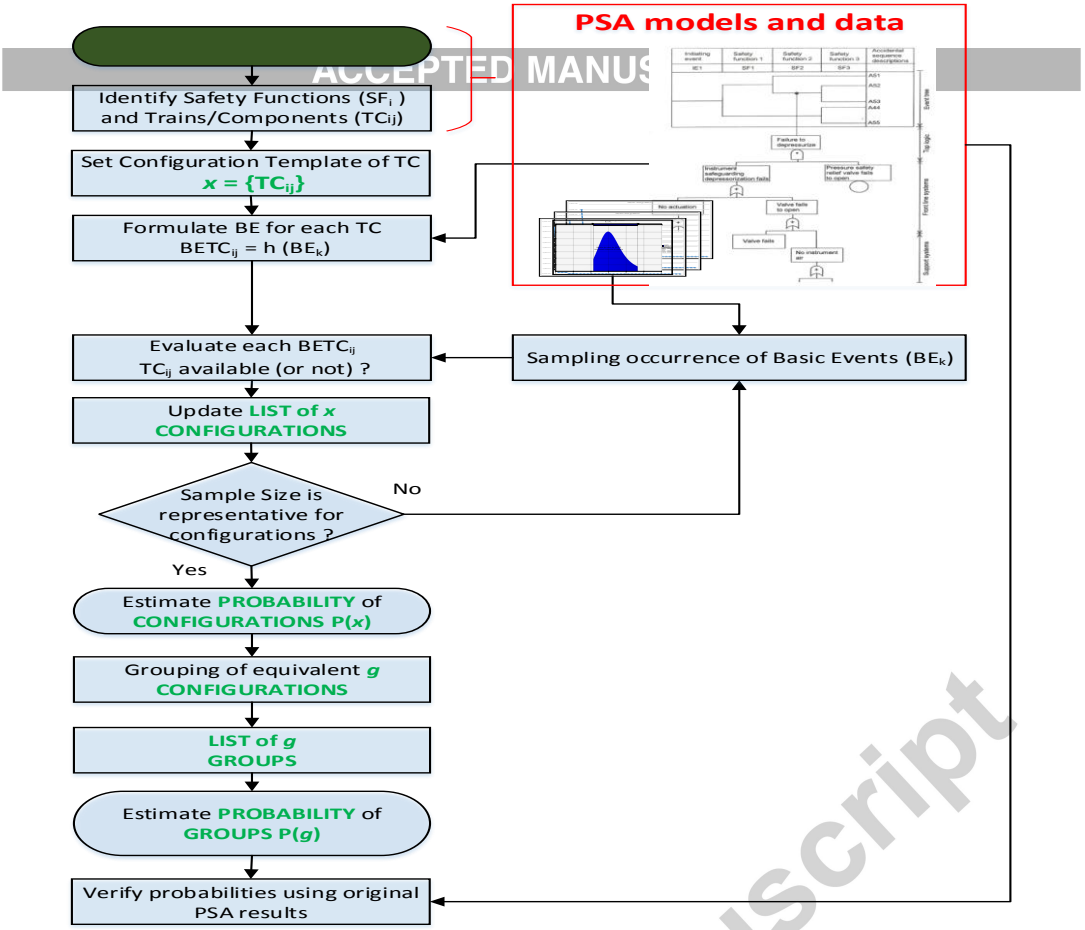

Figure 1. Approach to identify and associate probabilities for safety systems configurations

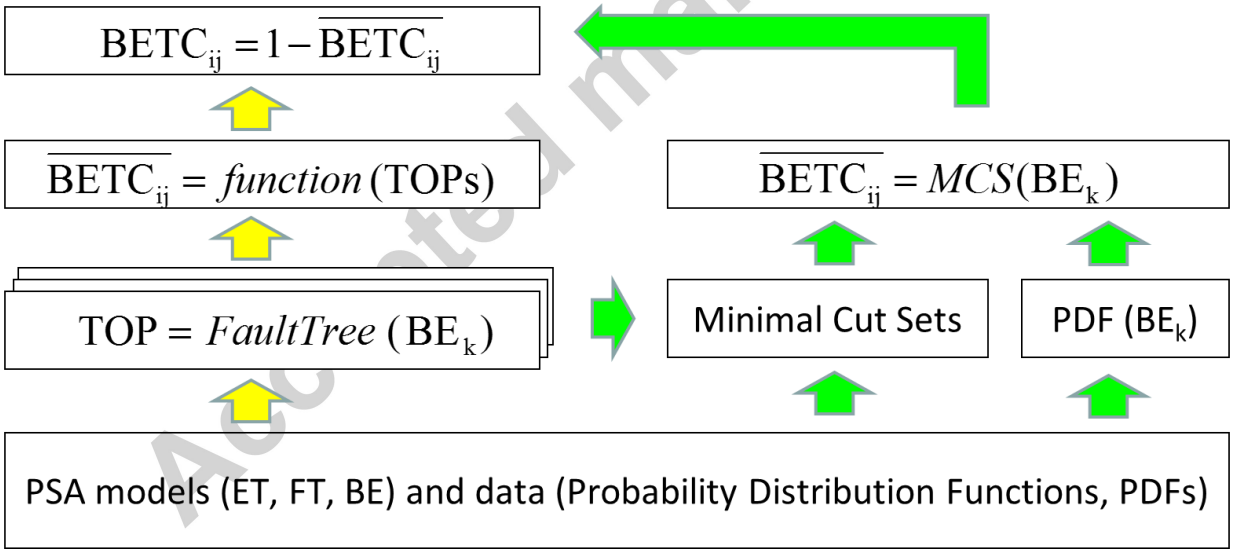

Figure 2. Approach to obtain Boolean equations of TC$_{ij}$

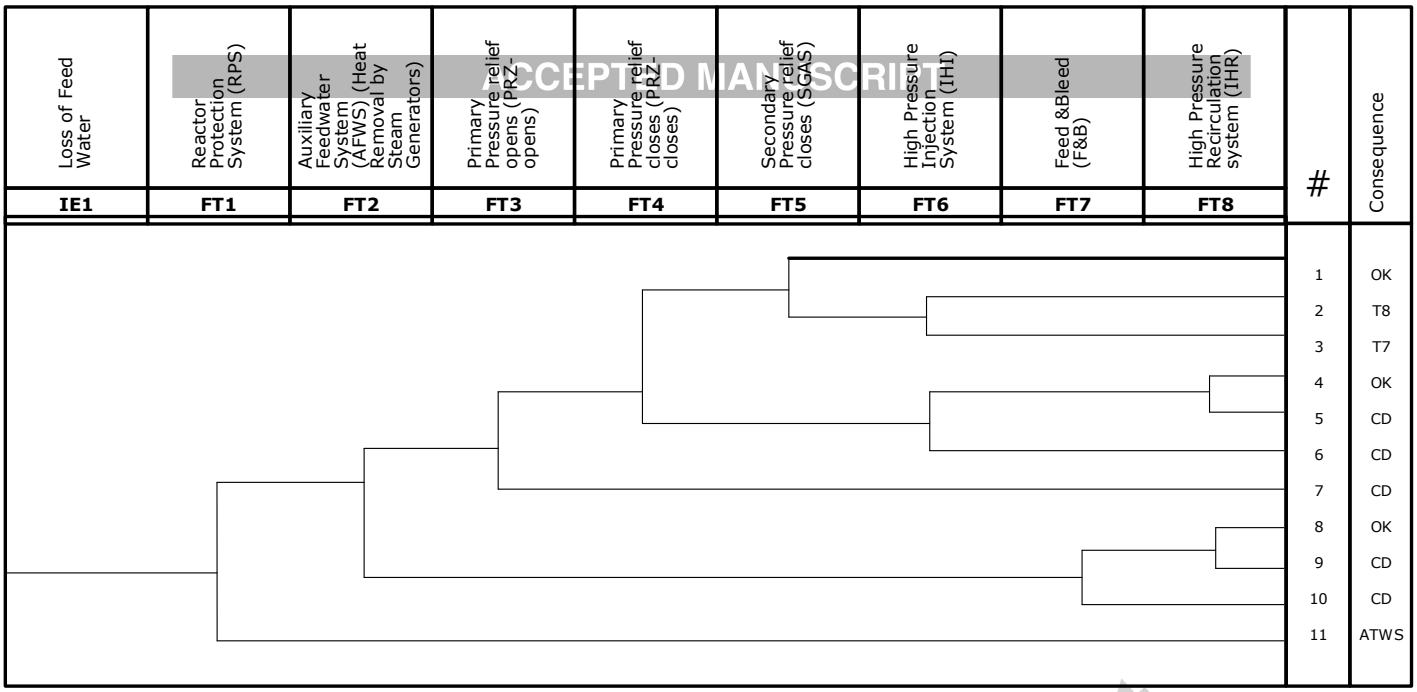

Figure 3. Event Tree for the LOFW transient

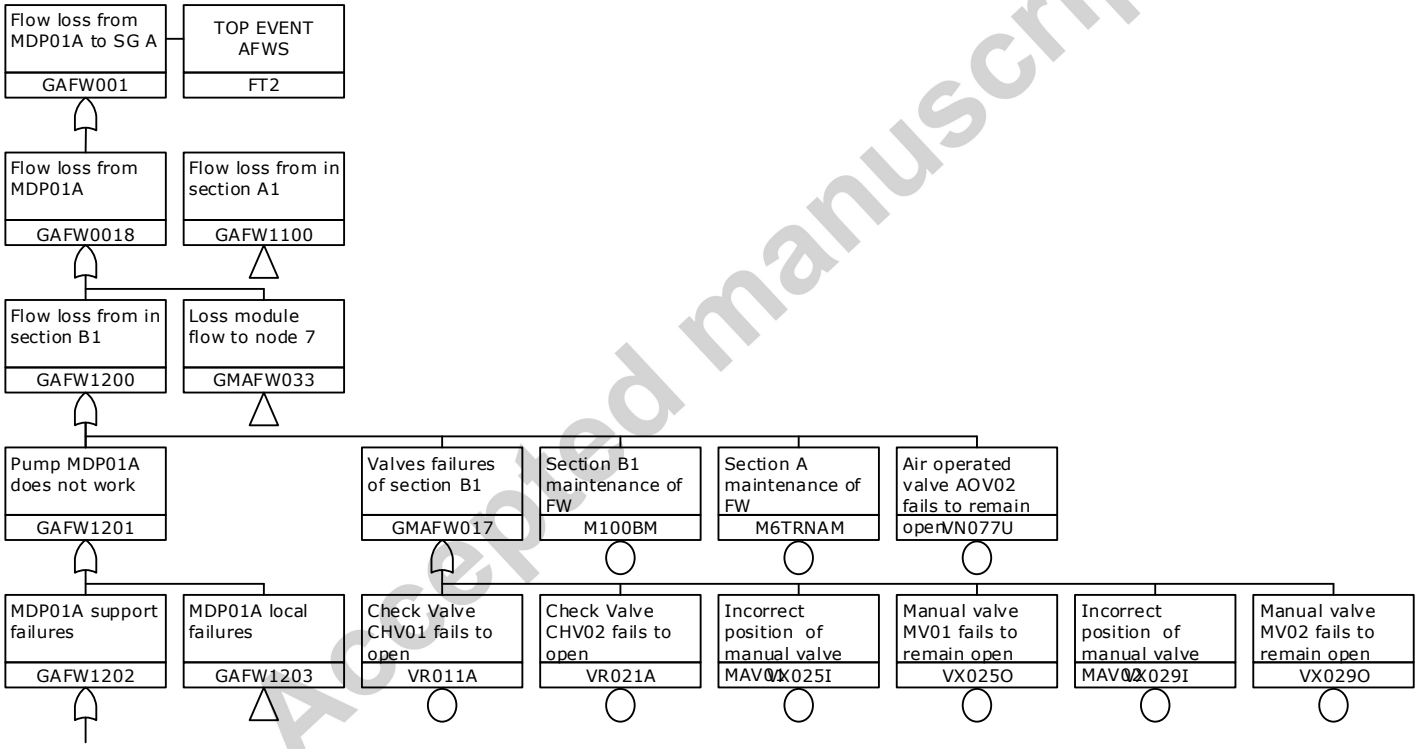

Figure 4. GAFW001 top event representing unavailability of the first of three redundant AFWS trains

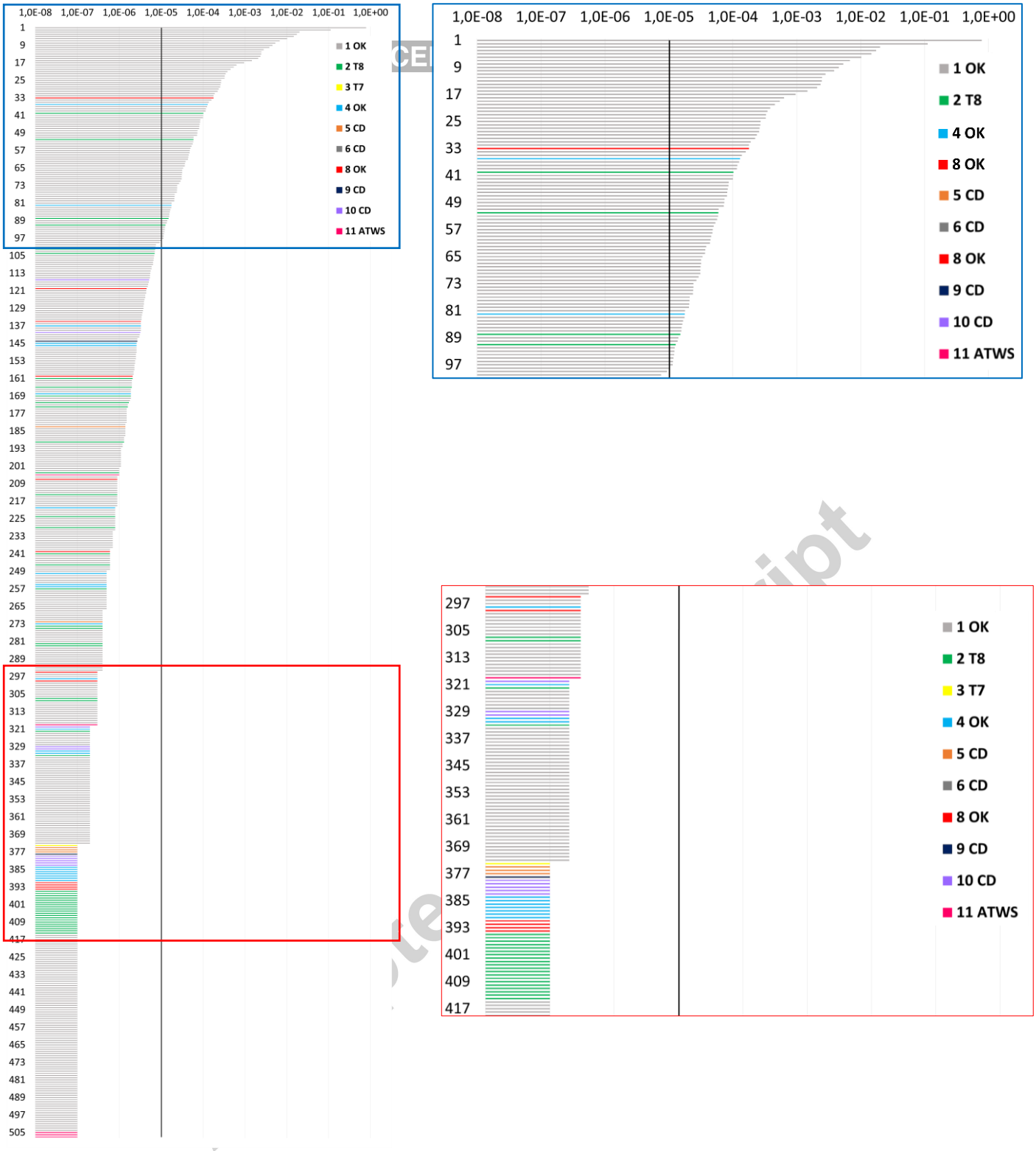

Figure 5. Plot of probabilities of groups of configurations and AS to which they belong (see Figure 3 also)

Table 1. Safety functions and success criteria required for LOFW. Relevant trains/components functions.

Header	SFi	Success Criteria	TCij
FT1	RPS	Two RPS channels	K
FT2	AFWS	1/3 AFW trains	AFW1, AFW2, AFW3
FT3	PRZ-opens	1/2 PORV or 1/3 SV open (o)	PORV1o, PORV2o, SV1o, SV2o, SV3o
FT4	PRZ-closes	2/2 PORV or 3/3 SV close (c)	PORV1c, PORV2c, SV1c, SV2c, SV3c
FT5	2SG-closes	3/3 MSIV and 8/8 SD close (c)	SD1c, SD2c, SD3c, SD4c, SD5c, SD6c, SD7c, SD8c, MSIV1c, MSIV2c, MSIV3c
FT6	IHI	1/3 IHI trains	IHI1, IHI2, IHI3
FT7	FB	1/2 PORVm & 1/3 FBIHI	PORV1mo, PORV2mo, FBIHI1, FBIHI2, FBIHI3
FT8	IHR	1/3 IHR trains	IHR1, IHR2, IHR3

Table 2. TOP events and basic events related to safety trains and components.

TOP-TC_{ij}	**GKTOP**	**GAFW001**	**GAFW002**	**GAFW003**	**GPORV025**	**GPORV026**	**GSV010**	**GSV011**	**GSV012**	**GPORV007**	**GPORV005**
K	**X**										
AFW1		**X**									
AFW2			**X**								
AFW3				**X**							
PORV1o					**X**					**X**	
PORV2o						**X**				**X**	
SV1o							**X**				**X**
SV2o								**X**			**X**
SV3o									**X**		**X**
PORV1c											
PORV2c											
SV1c					**X**	**X**				**X**	
SV2c					**X**	**X**				**X**	
SV3c					**X**	**X**				**X**	
SD1c											
SD2c											
SD3c											
SD4c											
SD5c											
SD6c											
SD7c											
SD8c											
MSIV1c											
MSIV2c											
MISV3c											
IHI1											
IHI2											
IHI3											
FBIHI1											
FBIHI2											
FNIHI3											
PORV1mo											
PORV2mo											
IHR1											
IHR2											
IHR3											

1HFSPO	**GPORV085**	**GPORV**	**GSV150**	**GSV151**	**GSV152**	**1SD008AC**	**1SD008BC**	**1SD008CC**	**1SD008DC**	**1SD008EC**	**1SD008FC**	**1SD008GC**	**1SD008HC**	**GSD351**

X												
X												
	X											
		X										
X			X									
X				X								
X					X							
						X						X
							X					X
								X				X
									X			X
										X		X
											X	X
												X
												X
X												
X												

GMSIVA	GMSIVB	GMSIVC	1HFMSI-VCM	GIHIR1	GIHIR2	GIHIR3	GIHTO-PINJ	1FOFEDYBLH	GPORV050	GPORV051	1VPPORVSL	GIHTO-TO-PREC

X			X											
	X		X											
		X	X											
				X			X							
					X		X							
						X	X							
				X			X	X						
					X		X	X						
						X	X	X						
								X	X		X			
								X		X	X			
				X									X	
					X								X	
						X							X	

Table 3. MCS corresponding to GAFW001 in terms of basic events.

MCS	Frequency	%	Equation
1	8.82E-03	27.51	VE52AR
2	8.58E-03	26.78	VK001O
3	3.04E-03	9.49	VK001F
4	2.92E-03	9.11	IH02AC
5	1.46E-03	4.55	CF001I
6	1.24E-03	3.87	M100B1M
7	1.20E-03	3.74	BM02AR
8	7.81E-04	2.44	VM035O
9	7.41E-04	2.31	VE52AS
10	4.48E-04	1.40	M500A1M
11	3.65E-04	1.14	BM02AS
12	3.00E-04	0.94	BM002L
…	…	…	…
	3.24E-02		

Table 4. PDF of basic events BE_k of GAFW001 form original PSA data.

BEk	Description	Probability Distribution Function (PDF)		Unavailability Model	Failure rate	T or TM [hours]	Unavailability
		Type	Parameters				
VE52AR	Fan 52 fails to operate	Gamma	α=4,00 β=10.854,52	Mission	3,69E-04	24	8,86E-03
VK001O	Motor-operated valve 01 fails to remain open	Gamma	α=3,00 β=802,55E+03	Standby	3,74E-06	13140	2,46E-02
VK001F	Motor-operated valve 01 fails to operate	Gamma	α=2,00 β=15,76E+03	Mission	1,27E-04	24	3,05E-03
IH02AC	Switch of Pump 02A fails to close	Beta	α=8,00 β=2,742E+03	Demand	2,92E-03	--	2,92E-03
CF001I	Defective Calibration of channel 01	Log-Normal	Mean=1,46E-03 EF=10,00	Demand	1,46E-03	--	1,46E-03
M100B1M	Maintenance of section B1	Log-Normal	Mean=1,24E-03 EF=3,00	Demand	1,24E-03	--	1,24E-03
BM02AR	Motor-driven pump 02A fails to operate	Gamma	α=29 β=579,59E+05	Mission	5,00E-05	24	1,20E-03
VM035O	Motor-operated valve fails to remain open	Gamma	α=1,5 β=12,57E+06	Standby	1,19E-07	13140	7,82E-04
VE52AS	Fan 52 fails to run	Beta	α=2 β=2.698	Demand	7,41E-04	--	7,41E-04
M500A1M	Maintenance of section A1	LogNormal	Mean=4,48E-04 EF=3,00	Demand	4,48E-04	--	4,48E-04
BM02AS	Motor-driven pump 02 fails to run	Beta	α=1 β=2,741 E+03	Demand	3,65E-04	--	3,65E-04
BM002L	Common failure cause to run motor-driven pump 02A/B	Beta	α=0,5 β=1,67E+03	Demand	3,00E-04	--	3,00E-04

Table 5. List of Safety Systems configurations, x_n, and corresponding probabilities, P(x_n).

K	AFW1	AFW2	AFW3	PORV1o	PORV2o	SV1o	SV2o	SV3o	PORV1c	PORV2c	SV1c	SV2c	SV3c	SD1c	SD2c	SD3c	SD4c	SD5c	SD6c	SD7c	SD8c	MSIV1c	MSIV2c	MSIV3c	IHI1	IHI2	IHI3	PORV1mo	PORV2mo	FBIHI1	FBIHI2	FBIHI3	IHR1	IHR2	IHR3	AS	P(x)	Cumulative probability
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	7,831E-01	7,831E-01
1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	6,105E-02	8,442E-01
1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2,507E-02	8,692E-01
1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2,487E-02	8,941E-01
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1,743E-02	9,115E-01
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1,021E-02	9,218E-01
1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	4,890E-03	9,266E-01
1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	4,904E-03	9,315E-01
1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	4,841E-03	9,364E-01
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	3,827E-03	9,402E-01
1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3,396E-03	9,436E-01
1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3,364E-03	9,470E-01
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2,527E-03	9,495E-01
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2,540E-03	9,520E-01
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1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2,491E-03	9,595E-01
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2,493E-03	9,620E-01
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2,495E-03	9,645E-01
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2,481E-03	9,670E-01
1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2,445E-03	9,695E-01
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1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	7,027E-04	9,825E-01
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	6,950E-04	9,832E-01
1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	5,001E-04	9,837E-01

Table 6. List of groups of equivalent configurations of safety systems, x_n, and probabilities, P(x_n).

K	AFW	PORVo	SVo	PORVc	SVc	SDc	MSIVc	IHI	PORVmo	FBIHI	IHR	AS	P(*g*)	Cumulative probability
1	3	2	3	2	3	8	3	3	2	3	3	1	7,831E-01	7,831E-01
1	2	2	3	2	3	8	3	3	2	3	3	1	1,110E-01	8,941E-01
1	3	2	3	2	3	7	3	3	2	3	3	1	2,004E-02	9,142E-01
1	3	2	3	2	3	8	3	3	0	0	3	1	1,743E-02	9,316E-01
1	3	2	2	2	3	8	3	3	2	3	3	1	1,463E-02	9,462E-01
1	3	2	3	2	3	8	3	3	2	3	0	1	1,021E-02	9,564E-01
1	3	1	3	2	3	8	3	3	2	3	3	1	6,760E-03	9,632E-01
1	1	2	3	2	3	8	3	3	2	3	3	1	5,319E-03	9,685E-01
1	3	1	3	2	3	8	3	3	1	3	3	1	4,521E-03	9,730E-01
1	3	2	3	2	3	8	0	3	2	3	3	1	3,828E-03	9,769E-01
1	2	2	3	2	3	7	3	3	2	3	3	1	2,798E-03	9,797E-01
1	2	2	3	2	3	8	3	3	0	0	3	1	2,475E-03	9,821E-01
1	3	2	3	2	3	0	3	3	2	3	3	1	2,445E-03	9,846E-01
1	3	2	3	2	3	8	2	3	2	3	3	1	2,349E-03	9,869E-01
1	2	2	2	2	3	8	3	3	2	3	3	1	2,083E-03	9,890E-01
1	2	2	3	2	3	8	3	3	2	3	0	1	1,472E-03	9,905E-01