CURRENT STATUS AND APPLICATIONS OF ISA (INTEGRATED SAFETY ASSESSMENT) AND SCAIS (SIMULATION CODE SYSTEM FOR ISA)

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The paper reviews current status of the Integrated Safety Assessment (ISA) unified approach, as well as the associated SCAIS (Simulation Codes System for ISA) computer platform. They are the result of a collaborative action among CSN, UPM and NFQ S.L, aimed at allowing the independent regulatory verification of the industry quantitative risk assessments.

This paper elaborates on the classical treatment of time in conventional PSA sequences and states important conclusions on how to avoid systematic and unacceptable underestimates of failure frequencies and other limit exceedance frequencies. The unified ISA method affords this challenge by coupling deterministic and probabilistic methods and accounting for their mutual influence.

The feasibility of the approach is illustrated with some application examples to real size plants.

I. INTRODUCTION. CSN/MOSI QUANTITATIVE SAFETY ASSESSMENT METHOD TO VERIFY CONCLUSIONS OF PSA INFORMED INDUSTRY SAFETY ASSESSMENTS

The two traditional approaches to safety analysis in nuclear power plants are the so-called Deterministic Safety Assessment (DSA) and Probabilistic Safety Assessment (PSA). DSA continues to be the main support for licensing design issues. However, at the post-TMI times, PSA started to be used as well in several licensing applications. The question of the consistency of deterministic and probabilistic studies was already posed in different licensing groups and reflected in the following issues:

(1) To which extent and at what stage of the PSA a significant change in stand-by safety systems initiation set-points, with obvious impact in DSA, could be reflected in PSA.
(2) To which extent both DSA and PSA covered different operator behaviours, including for instance, time delays in the manual actions.

CSN makes intensive use of PSA models in key aspects of its licensing day to day life, including inspection planning and categorization of their findings, incident analysis as well as operational aspects (maintenance rule, human reliability and safety culture). On the other hand, the operation is constrained by the conclusions of the analysis of the (automatic) design basis transients and accidents, (DSA), as reported in the safety assessments (SAR), that also include day to day requirements like those included in the Operating Technical Specifications (OTS). The overall process encompasses widely different safety studies in nature, data, phenomena and systems, each being a piece interacting in several ways with many others.

Ensuring the consistency among implicit and explicit assumptions, interfaces and conclusions is a major task of the regulatory review. The set of activities may be considered as a licensing Validation and Verification (V&V) process. Most regulatory activities are qualitative in nature, but the widespread use of computerized analysis also requires sophisticated, quantitative V&V with independent checks complementing the qualitative process. This paper summarizes some of the tools (SCAIS) and methods (ISA) that have been (and are being) developed at CSN for this purpose and some of their results, with special emphasis in the most recent developments. The main focus is in PSA related topics that may be classified according to the three main stages of a typical PSA, namely:

1. Delineate the possible sequences of events (SOE), which amounts to find all possible Sequences of dynamic Transitions (SOTs) resulting from the sequence of protective actions as well as possible failures of safety systems. Any protective action does not take place unless necessary conditions for it are fulfilled, most often consisting of process variables entering certain regions, situations that we call stimulus activations, like triggering alarms, reaching procedure entry points and/or crossing deterministic setpoints. The set of transients where some stimulus becomes activated is called here the domain of that stimulus.
2. Determine system success criteria, discriminating successful sequences of configurations of the safety systems (i.e., those where the wrong trends of damage indicators are successfully corrected) from failed ones. As an addition to classical PSA, it is possible to identify in the uncertainty space of each sequence the conditions leading to activation of failure (damage) indicators, giving rise to the concept of failure (damage) domain.
3. Compute, for each SOE, the frequency resulting from its safety systems configurations, by using, for instance, FT/ET techniques. In the case that failure (damage) domains are identified in the sequence, the corresponding failure (damage) frequencies can also be computed.

While detailed methods and abundant literature [1] provide guidance for sequence frequency computation in stage 3, such a guidance becomes loose when describing stages 1 and 2, mainly due to the unique phenomena involved in each application domain, their strong nonlinearities, and their dependence on the protection design methods, usually very sophisticated and technology dependent as described in Safety Analysis Reports (SAR) [2].

The paper addresses the feasibility of the ISA-SCAIS approach and, in addition, presents new ideas to handle the important event timing and boundary conditions uncertainty, allowing for dividing/synthesizing the main ingredients of the accident progression.

II. ISA-TSD METHODOLOGY

As indicated, ISA tries to verify compliance with regulations and consistency in the design and safety assessments made by industry. Consistently with this intend, ISA is an integrated method where deterministic and probabilistic aspects of the safety problem are solved together, taking into account mutual dependencies.

The concept of sequence as an ordered set of events is also extensively used in ISA. The ISA methodology strongly relies on simulation to determine the consequences of accident sequences. However, a sequence cannot be assimilated to a particular time history. Treatment of sequence uncertainties and identification of failure domains are essential parts of ISA. If sequence success criteria are used, each simulated transient is evaluated against those criteria in order to find the failure domain. The concept of header success criteria is no longer needed since compliance with the sequence success criteria is not a function of the header success/failure states (as in classical PSA) but a direct result of the simulation. This allows for using ISA as a powerful tool to verify the header success criteria used in Level 1 PSA.

The main basis of the ISA-TSD method (Integrated Safety Assessment based on the Theory of Stimulated Dynamics, [3], [4], [5]) is to lower the assessment from the system configuration sequence level, characteristic of Level 1 PSA, or from the envelope level, characteristic of DSA, to the transient level within each sequence by:

1) Considering sequences as large groups of transients accounting for all the relevant uncertainties, e.g., parameter uncertainty, initial conditions, variability in occurrence time of events and uncertainty in boundary conditions.
2) Simulating a number of those sequence transients in order to find the sequence failure domain, defined as the subset of sequence transients in the uncertainty space ending in a failed state. The number of transients that need to be simulated depends on the desired accuracy of the failure domain characterization but, in general, this number is very high.
3) Providing TSD algorithms to compute the contribution to the failure frequency (i.e., to the exceedance frequency of the safety limit used to define the failed state) of any transient belonging to the failure domain, then aggregating these contributions for all the transients there. Included as factors in those algorithms are the conditional probabilities of the safety system configurations characteristic of Level 1 PSA. Explicit consideration of stimuli ensures consistency of the set of safety measures included in every transient and allows for a proper classification of transients into dynamic sequences.

III. SCAIS (SIMULATION CODES SYSTEM FOR ISA)

Leaving aside the theoretical aspects that inspire the detailed computational methods (TSD, [3], [4], [5]), ISA analysis involves a lot of transients, and its application then requires a set of simulation/computational tools. The computerized platform called SCAIS has been developed for this main purpose. It is composed by a set of interconnected modules which, nevertheless, have their own entity and can be used as standalone tools or as modules of other methods as well.

Present day SCAIS (see [4], [5] for its evolution) is the result of a consolidation and modernization program of prior systems. It is being developed in close collaboration with NFQ Solutions S.L., a software development company specialized in risk assessment. Also, the Technical University of Madrid (UPM) actively participates at the testing and application level.

Because the focus of the ISA setup is the Dynamic Event Tree (DET) approach, transient simulation plays a fundamental role and most of the components of SCAIS are transient related, i.e., deterministic, while a few others are probabilistic in nature. Figure 1 presents a simplified scheme of the ISA-TSD methodology whose blocks parallel the main components of SCAIS.

The “Automatic Generation of Paths/Sequences” block in Fig. 1 includes the following SCAIS elements (see [4], [5]):

(1) BABIECA is the general simulation driver. It combines internal and external simulation modules from which the user can configure the plant model in the form of a topology of interconnected modules (see [6]). It takes care of the overall solution by controlling the transmission of information among modules, solving feedback loops if they exist and advancing the time step. These features provide a great flexibility to build powerful plant simulation models.

(2) DENDROS (see Fig. 2) is the event scheduler that drives the dynamic generation and management of the different event sequences resulting from a given initiating event. It directs the simulation to perform the systematic traversal of all the possible branches, leading to different sequences. DENDROS identifies and manages the branching points resulting from user-specified conditions for the occurrence of events and, if it is the case, asks BABIECA to open new simulation processes, one for each possible outcome of the event (Fig. 2). The result is a Dynamic Event Tree (DET).

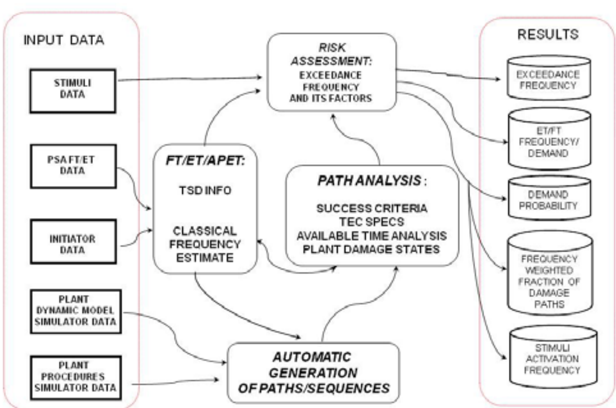

Fig. 1. Simplified scheme of the ISA-TSD methodology

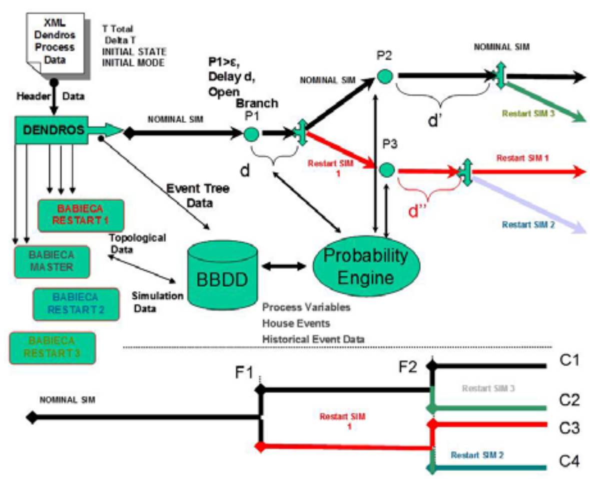

Fig. 2. Overall BABIECA-DENDROS-probability calculator coordination

(3) PLANT MODELS. A plant model is a particular user-defined combination of BABIECA modules able to simulate accident sequences. The variety of plant models that can be configured ranges from using well accepted and validated external codes (MAAP, TRACE) to those composed only by internal BABIECA modules.

(4) SIMPROC is the simulator of operating procedures which interacts with BABIECA to implement the operator actions requested by the procedures (see [7]). It is a special case of BABIECA external module because of the particularities of the interaction between plant and procedures.

These four SCAIS components implement the main dynamic modules as required for DET deployment, including also those allowing for the verification of procedures via automatic pilot simulations. Other SCAIS components are the following:

(5) The PROBABILITY CALCULATOR (ET/FT/APET block in Fig. 1) is actually a collection of methods and algorithms that provide probabilistic quantifications. It may be optionally called to make estimates of the respective probabilities of the output branches of a branching point and to use them for elimination of some of these branches on the basis of low probability termination criteria. Its major role is the computation of exceedance frequencies in coordination with the RISK ASSESSMENT module.

(6) PATH ANALYSIS MODULE (Fig. 1), which performs the detailed analysis of individual event tree sequences through the simulation of specific transients (paths) of the analyzed sequence. In coordination with DENDROS, the PATH ANALYSIS MODULE defines multiple simulation cases, i.e., sequence paths, by varying values of uncertain parameters and/or time delays (human actions or stochastic phenomena). The aim is to identify the sequence failure domain.

(7) The SCAIS DATA BASE is a SQL relational data base (POSTGRES SQL) used as a repository for input and output information. Represented by the left-hand and right-hand side columns in Fig. 1, it stores all the input data and results allowing their easy post-processing. The information stored in the data base can be accessed off-line making it possible to perform new analyses on the existing data without repeating the simulations unless necessary.

(8) The RISK ASSESSMENT module, also shown in Fig. 1, calculates the frequency of the failed states, by integrating the TSD equations over the failure domain obtained from the PATH ANALYSIS MODULE, and considering the frequency density functions obtained from the probability distributions evaluated in the PROBABILITY CALCULATOR.

All main components of SCAIS, including the simulator driver BABIECA and the event scheduler DENDROS, are designed with object oriented architecture and implemented in C++ language. The whole SCAIS has been developed using open source standards (Linux, XercesC, libpq++) trying to make it platform independent.

Automatic generation of DETs is only possible with an adequate coordination between BABIECA and DENDROS and, sometimes, also coordinated with the PROBABILITY CALCULATOR. Figure 2 illustrates the branching procedure implemented in SCAIS. For the sake of simplicity, only binary branching points are represented where the two output branches correspond to occurrence or not of an event. The upper part of the figure represents the opening of new simulation processes while the lower part represents the corresponding dynamic event tree resulting from this procedure.

Branching criteria are represented by P_i (P_1, P_2, etc) in this figure. They correspond to stimulus activations and the branching consists of simulating both the occurrence and the non-occurrence of the event. When DENDROS detects that a branching criterion has been reached it initiates the branching procedure, possibly delayed by a time d if so specified in the branching rules. First, DENDROS asks BABIECA to generate a restart file with the current status of the simulation and the existing simulation process continues with the “nominal” option (occurrence or non-occurrence of the event, depending on the defined branching rules). Second, DENDROS spawns a new simulation process, i.e., another instance of BABIECA, initializing the simulation model with the stored restart file and forcing the “alternative” option of the branching point. This procedure is recursively continued until every simulation process meets some predefined termination criterion.

IV. RECENT ACTIVITIES

IV.A. Summary of Activities in the Deterministic Side

IV.A.1. ISA methods used for sequence delineation and quality of the set of Design Basis Transients used in SARs (envelope issue)

PSA-DSA in the nuclear context is but another example of optimization of adequate protections and its verification. The main problem is to find envelopes of the evolution of damage indicators in sequences of successive changes in dynamics, (i.e., SOT), associated to protection actions. In general, the problem focuses on ensuring that the envelopes consider all the possible SOT that may be involved in the accident progression and then cover, for each sequence, uncertainty in initial conditions and key data, as well as, most important, boundary conditions and protective actions timing. These uncertainties easily explode the number of situations to consider, so that brute force techniques based on reproducing transients with best estimate simulations usually fail in the completeness of the situations considered to demonstrate the (umbrella) enveloping character.

Figure 3 deploys the strategies followed by the nuclear industry, as well as by CSN/MOSI, to ensure that all relevant situations are covered, including the division in sub-problems accounting for the accident progression (APET, [5]).

The SAR underlying philosophy is consistent with figure 3, but this approach uses the concept of “design basis transients/accidents” in order to cover all automatic action design situations. This implies the use of artificial events distorted both in assumptions and models, so that the timing of these analyses is also artificial. It is not simple to see the equivalence with the sequence delineation in PSA because of the different purpose. Any PSA invoking SARs should be aware that they provide no clue to answer important issues as the available times embedded in the success criteria. Neither they guarantee the sequence delineation, stage 1, that requires extensive PSA additional analysis, based on safety functions, taking into account that out of design situations are also considered, including operator actions.

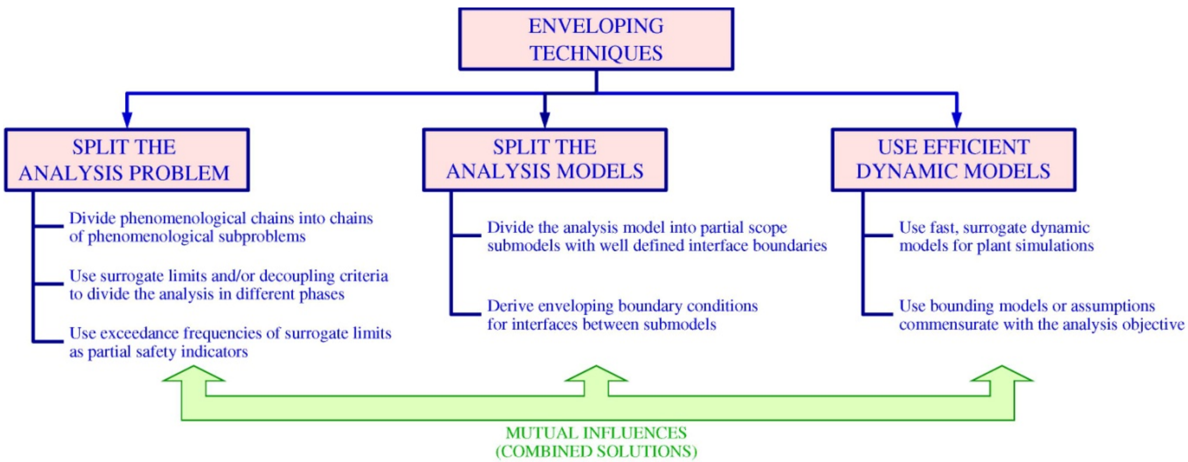

Figure 3. Strategy to ensure that all safety relevant situations are covered.

Instead, the ISA-SCAIS verification method considers sequences as piecewise objects (one piece for each interval between consecutive transitions) consisting of well identified groups of transients covering all uncertainties in an explicit way, including time of actions and dynamic model boundary conditions as functions of time. The design domain of DSA is therefore clearly distinguished from the general risk domain of PSA.

References [4] and [5] detail tools, methods and several examples describing the ISA-SCAIS V&V approach for internal consistency of the deterministic analysis and the verification of the sequence delineation, that is, stage 1. The method proposes the use of surrogate models, fed from the deterministic analysis, to analyze sequences. When considering deterministic–probabilistic consistency of stages 2 and 3, the approach ends up in the generation of a SCAIS data base of an adequate, best estimate set of representative transients and the corresponding identification of dynamic surrogate models. These surrogate models consistently carry the deterministic connection while allowing for fast simulation of a myriad of transients, each stimulus variable having a different surrogate model that projects the influence of the rest of the system.

IV.A.2. Verification of Emergency Operating Procedures (EOP) and Severe Accident Management Guides (SAMGS)

When verification of an emergency procedure (EOP) for scenarios without core melt is the issue, simulations are run with an automatic pilot version of the procedures, as realistic as possible, by using our procedure simulator SIMPROC (see [7]) coupled to the automatic event tree simulator SCAIS. Timing to take the actions is predetermined using info from best practices and from operator crew task action studies. The objectives of the procedure should be met and success relative to any of the safety limits should be ascertained. If this is not the case, the procedure is questioned at specific points. Examples are given in reference [8]. They are part of the automatic sequence delineation verification of stage 1.

Concerning SAMGS, as a post Fukushima starting activity, MOSI engaged in methods to get useful insights about severe accident scenarios with special emphasis on Station Blackout (SBO). As a preliminary exercise the SCAIS platform, using its MAAP system module, was used to analyze a SBO sequence with failure of Reactor Coolant Pump Seals (Seal LOCA) in one of our three loop PWR-W plants (see [9]). The set of actions is depicted in figure 4 below that identifies the emergency procedures and Severe Accident Guides involved. Battery depletion is assumed to result in loss of DC power before the eventual AC recovery which implies also recovery of the DC electric power. Five damage indicators have been considered in the analysis (listed by increasing severity):

- Core uncovery
- Core Exit Temperature (CET> 922 K)
- Peak cladding temperature (PCT > 1477 K)
- Fuel relocation into lower plenum
- Reactor Pressure Vessel (RPV) failure.

Figure 5 shows the damage domains for this sequence obtained when considering time uncertainty in both loss of DC and recovery of AC-DC. The color of each point represents the most severe damage indicator reached along the corresponding simulation run. Black points represent transients with RPV failure. A total of 900 simulations were run, each providing the information of one of the (uncertain) time combination points of the figure. The analysis provides some clues on the adequacy of the Fast Cooling AM strategy in this kind of scenarios.

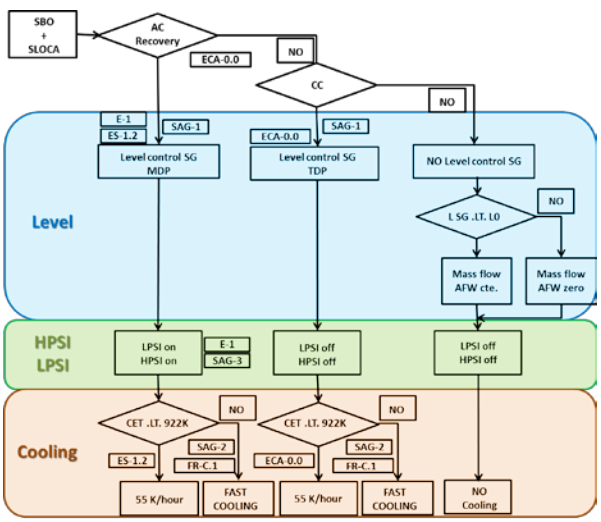

Figure 4. Main operator actions taken into account in SBO sequences with Seal LOCA.

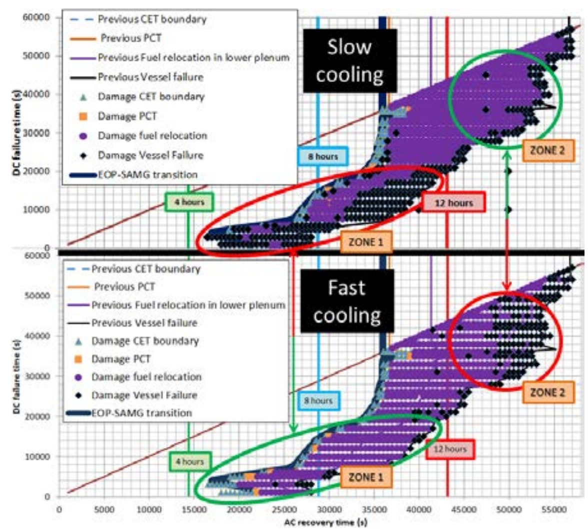

Figure 5. Comparison between damage domains with slow and fast cooling

IV.B. Summary of Developments and Applications in Classical Probabilistic Issues

IV.B.1. Incident analysis

CSN/MOSI has direct responsibility in executing the CSN incident analysis on a routine basis using a customized, classical FT/ET method in order to rank their severity and to classify them as precursors of more severe situations.

Precursor analyses [10] are performed in the framework of the Incident Revision Panel (IRP). The IRP is a cross-disciplinary group that discusses, reviews and classifies every incident reported by the Spanish NPPs to CSN. Within this group, precursor analyses are requested to obtain a measure of the risk impact associated with the incident and to have a probabilistic criterion as an input to the classification. An incident with a risk measure (Conditional Core Damage Probability, CCDP) larger than 10^{-6} is a precursor; and an incident with a CCDP larger than 10^{-5} is a significant precursor, and is then classified as a significant event. Insights from precursor analyses are discussed within this group.

This precursor activity has evolved over the years in scope (also covering Significance Determination of inspection findings) and MOSI involvement as more PSA models were available. Some overall results are presented in figure 6.

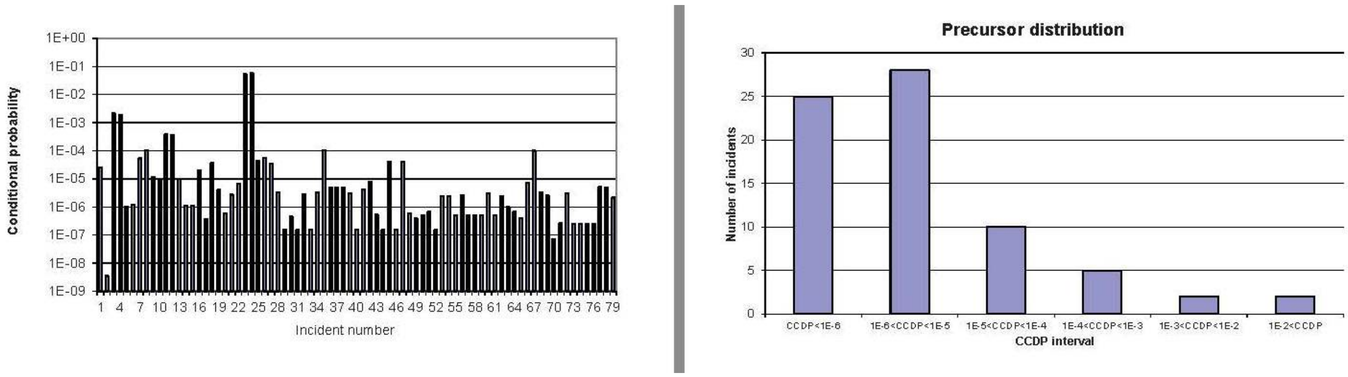

Figure 6. Results of Precursor Analysis. Precursor Distribution.

IV.B.2. Probabilistic consistency across different plants. Verifying classical FT quantifications

The cumulated MOSI experience in FT/ET quantification of Spanish plants with industry PSA models, include the use of, and knowledge about, different computational platforms (substantially Risk Spectrum and CAFTA), and different modeling cultures at the different plants. As exemplified in the case of the precursors and significance determination of inspection findings, inter-comparison between results in these different contexts is essential to better understand the risk profiles of the plants. However, sometimes doubts appear about whether or not the same problem would give similar results in different computational environments. In view of this, MOSI, in cooperation with the CSN PSA licensing branch, initiated an important harmonization activity. It is based on the use of tools (already available where they existed, and internaly developed where they did not) translating the different modeling formats into a unified XML language (Open PSA initiative) (see [11]). Additionally, tools were also used/developed to translate the unified XML input files back to either computing environment. In addition, research projects were launched to verify the efficiency of the computations by comparison with other approaches, alternate to ET/FT. Among them, Binary Decision Diagrams (BDD) constitute a popular alternative and one of the projects (see [12]) used them for this purpose.

Furthermore, as a regulator, CSN staff needs independent views on licensee models, which asks for in-house made models. This is a harmonization activity which unifies different modeling techniques and a diversity of hypothesis that are not intrinsic to and therefore not part of the risk profile. In this framework, the SPAR (Standardized Plants Analysis Risk) concept, taken from the approach followed by USNRC in its regulatory system, is being studied and analyzed by CSN in collaboration with UPM, with the aim to attain a standard modeling framework and overcome the problems and drawbacks appeared in regulatory applications during last years. The strategy followed is based in the comparison of current PSAs of similar Spanish NPP in order to collect, identify and agree on which characteristics, hypothesis and modeling approaches (both at ET and FT level) are most adequate and convenient for CSN as standards for in-house modeling (see [13]).

V. OTHER CURRENT DEVELOPMENTS

V.A.1.ISA-TSD off-line prototype

ISA-TSD framework has a deterministic aspect, namely, finding the damage (failure) domains and a probabilistic one, namely, finding their frequency. The SCAIS transient simulation techniques described above do not include the strategy to optimize the branching approach of the DET to minimize the number of runs needed to identify those damage (failure) domains. ISA-TSD extends the classical uncertainty methods (mostly referred to parameters) to uncertainty of the timing of events as well as to enveloping initial conditions, and boundary condition uncertainty.

Figure 7 shows the structure of an off-line TSD prototype aimed at testing experimental techniques for damage/failure domain searching and computation of the exceedance frequencies. This way, each research item looking for ISA/SCAIS improvements can be tested off-line before its final integration in SCAIS. The prototype performance has been exemplified under some challenging situations, such as the impact on the containment of an inflow of hydrogen and steam as a Level 2 PSA sub-problem, in a severe accident medium size LOCA scenario ([14, [15]). A totally different case, consisting on a plant transient analysis (SAR type) in an experimental facility, also showed the usefulness of the prototype and the unified character of the tools.

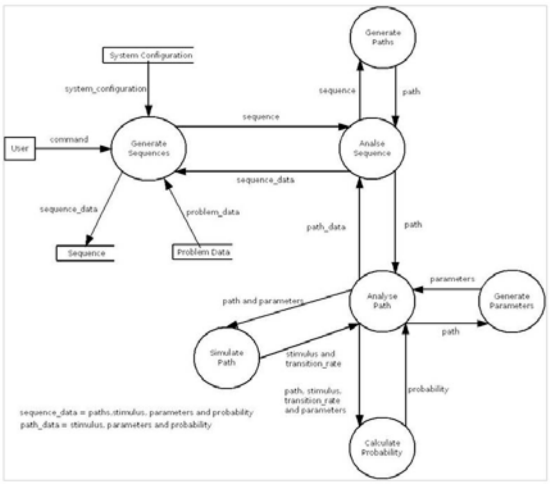

Fig. 7. Structural block diagram of the off-line TSD prototype.

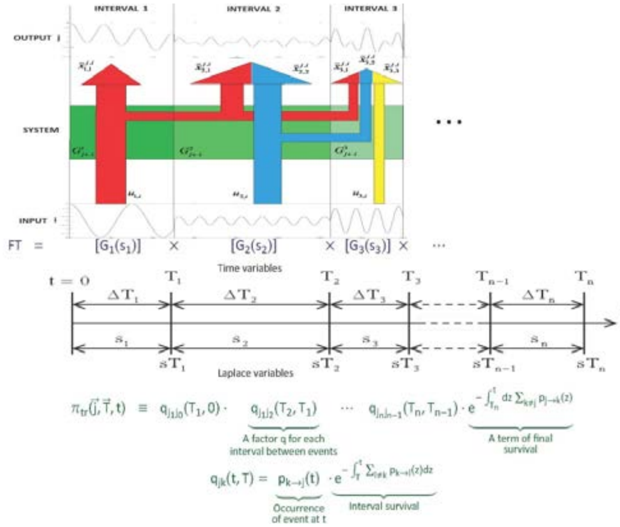

Figure 8. TFT+TSD approach.

V.A.2.TFT+TSD approach

ISA TSD method requires adequate dynamic models, able to find reasonable envelopes for any sub-problem describing accident progression phases in different areas of the plant. However, best estimate codes are too large and complex to be used directly and finding adequate models for each sub-problem is hard and difficult to validate, especially when considering the widely different phenomena involved from one sub-problem to another. CSN-MOSI is working on a new approach to tackle this.

Because the safety variables of interest are not that many, the idea is to use the BE multi-process-variable codes to identify and feed Envelope Surrogate Dynamic Models that are adequate to project and envelop the BE result on any preselected single process variable. The single process variable surrogate models are dynamic models based on piecewise linear approximations and have the same math structure in all cases. Very fast and efficient algorithms allow running the very many transients required to afford the timing and boundary condition envelopes. The basis for the dynamic surrogate models is the Transmission Functions Theory (TFT) ([5], [16]). Figure 8 depicts schematically the approach.

VI. ISA ROAD MAP DEVELOPMENT

Some research objectives that are foreseen within ISA-TSD-SCAIS development are the following:

- Future activities will continue to consolidate, optimize and gain more experience in the specific approach followed, including:
    - Implementation of regular PSA quantification methods and tools within SCAIS computer platform. The aim is to set up the use of current NPP Fault Trees models.
    - Generation of CSN standardized PSA models (like the USNRC SPAR models) of Spanish plants that may be quality graded.
- Different research initiatives will be devoted to improve and optimize the use of Dynamic Surrogate Models based on TFT within ISA-TSD methodology. Some examples are the following:
    - Explore the definition of several useful figures of merit to synthesize results of PSA dynamic assessments; e.g., header-importance indices that characterize its dynamic efficiency (i.e., the protective or degrading actual function of the header).
    - Development of Transmission Functions (FT) identification techniques based on data base (BE code or experimental results).
    - Application to estimates of source terms in PSA2, in a similar way as in the U.S. Nuclear Regulatory Commission (NRC) representative PSA2 study ([17]). These estimates include uncertainty bands for the release of the most important families of radio-nuclides.

- In the framework of the more general Integrated Deterministic and Probabilistic Safety Assessment (IDPSA) techniques being developed worldwide (see [18], [19]) some research activities can be expected:
    - Equip SCAIS with adequate data mining and classification techniques [20], which would help to establish lossless extraction and condensation of useful information amenable to expert evaluation. Here again TFT could play a relevant role.
- Further applications of the method (see [21], [22], [23], [24]) are still under consideration. In particular, ISA/SCAIS approach is having an interesting and direct applicability in the verification of SAMGs and EDMGs ([25], [9]).

VII. CONCLUSIONS

Quantitative V&V activities of industry supporting analyses at regulatory bodies are complementary of their qualitative reviews, and are essential in view of the ubiquity of computerized analysis included in the industry safety cases. Among the many issues involved, consistency checks are of primary importance. They require specific developments of independent tools and methods.

In particular these checks should be performed when they refer to the issue of probabilistic versus deterministic aspects which involves very difficult problems, as to verify success criteria and to discriminate when they should be consistently modified in PSA applications. For instance, relaxation of OTS (Operating Technical Specifications) justified on the basis of FT/ET computations should not be accepted without ensuring first that the FT/ET success criteria do not require consistent modifications.

We briefly described a part of the efforts made at CSN to develop diagnostic tools and methods for this purpose, focusing in the success criteria and internal consistency of the probabilistic side. This helps much in a technically objective regulatory decision-making since consistency of probabilistic and deterministic aspects can be better addressed.

The document has elaborated on a) the steps done in the development of the Integrated Safety Assessment (ISA) methodology and its associated software package (SCAIS); b) recent applications of the methods and tools that illustrate its potentiality to verify consistency of deterministic and probabilistic licensing safety cases; and c) further areas of development that are foreseen.

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