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RELIABILITY METHODS FOR PASSIVE SYSTEMS

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RELIABILITY METHODS FOR PASSIVE SYSTEMS

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TABLE OF CONTENTS

LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
BOPHR	Base Operation Passive Heat Removal
CDC	Critical flow Discharge Coefficient
CDF	Cumulative Distribution Function
ECCS	Emergency Core Cooling System
E.J.	Expert Judgment
E.T.	Event Tree
FORM	First Order Reliability Method
FMEA	Failure Mode and Effect Analysis
H-A	Hydro-Accumulator
HPIS	High Pressure Injection System
ICS	Isolation Condenser System
LPIS	Low Pressure Injection System
NN	Neural Network
PCC	Partial Correlation Coefficient
PDF	Probability Density Function
PRCC	Partial Rank Correlation Coefficient
PSA	Probabilistic Safety Assessment
RMPS	Reliability Methods for Passive Systems
RP2	Residual Passive heat Removal system on the Primary circuit
SORM	Second Order Reliability Method
SRC	Standardized Regression Coefficient
SRRC	Standardized Rank Regression Coefficient
T-H	Thermal-Hydraulic

EXECUTIVE SUMMARY

Within the framework of the RMPS project, a methodology has been developed to evaluate the reliability of Passive Systems characterized by a moving fluid and whose working is based on thermal-hydraulic (T-H) principles.

The methodology deals with the following problems:

- Identification and quantification of the sources of uncertainties and determination of the important variables.

The first step of the methodology is the definition of the accidental scenario in which the system will operate. Then the system can be characterised. The goal of this characterisation is to obtain information about the passive system behaviour, in an accident occurring during the life of the complete system and to identify the failure zones and conditions, if they exist. The missions of the system, its failure modes and the failure criteria are defined. Due to the lack of suitable experimental databases for passive systems in operation, the evaluation rely on qualified thermal-hydraulic system code performing best estimate calculations. The method requires the identification of the potentially important contributors to uncertainty of the code results. In the present study, the uncertainties pertaining to the code itself are not accounted for, focusing the attention on the uncertainties relative to the input parameters of the code, characteristic of the passive system or of the complete system. Among all the sources of uncertainties, the evaluation of the reliability of a passive system requires the identification of the relevant parameters which really affect the accomplishment of the target of the system. The tool here chosen for this task is the Analytic Hierarchy Process. An important feature of the methodology is the sensitivity analysis of the importance of parameter uncertainties for the uncertainty of the passive system performance. These sensitivity measures give a ranking of input parameters and provides guidance as to where to improve the state of knowledge in order to reduce the output uncertainties most effectively. In the methodology, the use of linear and non linear sensitivity indices are proposed.

- Propagation of the uncertainties through T-H models and assessment of T-H passive system unreliability.

In the methodology, two types of methods are proposed to quantify the reliability of the passive system once given a T-H model of the system: the Monte-Carlo simulation and the First and Second Order Reliability Methods (FORM/SORM). The Monte-Carlo simulation requires a large number of calculations and can be often prohibitive when each calculation involves a long and onerous computer time. To avoid this problem, two approaches are proposed: the variance reduction techniques in Monte-Carlo methods (Importance sampling, Directional simulation…) and the use of response surfaces where the physical model is replaced by a simpler mathematical model no leading to expensive computation costs.

- Introduction of passive system unreliability in the accident sequence analysis.

The objective of this part of the methodology is the development of a consistent approach for introducing passive system reliability in an accident sequence of Probabilistic Safety Assessments (PSA). The treatment of passive systems in PSA models is a difficult and challenging task. No commonly accepted practices exist so far on how reliability of passive systems can be taken into account. The main challenge arises from the nature of passive systems which main operating principles are based not on active components, but on physical phenomena. In a first approach, applied to a simplified PSA carried out on a fictitious reactor equipped with two types of safety passive systems, we have chosen an Event Tree (ET) representation of the accidental scenario. ET techniques allow identifying all the different chains of accident sequences deriving from the initiating events. The failure analyses performed on this reactor have allowed the characterisation of the technical failures (on valves, tubes in exchanger and safety injection check valves) and the ranges of variation of uncertain parameters which influence the physical process. The majority of the sequences of this event tree have been analysed by deterministic evaluations with envelope values of the uncertain parameters. For some sequences where the definition of envelope cases was impossible, basic events corresponding to the failure of the physical process have been added and uncertainty analyses have been performed to evaluate the corresponding probability of failure. For this purpose the thermal-hydraulic code has been coupled to a Monte-Carlo simulation module. The failure probabilities obtained by these reliability analyses have been integrated in the corresponding sequences. This methodology allows the probabilistic evaluation of the influence of the passive system on an accidental scenario and could be used to assess the interest to replace an active system by a passive system on specific situations.

In complement to this analysis, guidelines have been proposed for future improvements of the incorporation of passive systems in an accident sequence, within a PSA framework. These guidelines highlighted the need for the development of dynamic event trees, as compared to conventional PSAs which do not systematically model the dynamic aspects of accident progression, including dynamic system interactions and dependencies and thermal hydraulic phenomena induced failures. This requirement emerges from the consideration that thermal hydraulic natural circulation passive system operation is strongly dependent, more than other safety systems, on the state/parameter evolution of the system during the accident progression.

The methodology has been tested on 3 examples of industrial T-H passive system, the Isolation Condenser System of BWR, the Residual Passive heat removal system on the Primary circuit (RP2) of PWR and the Hydro-Accumulator of VVER-1000. The T-H calculations have been performed using the RELAP, ATHLET and CATHARE computer codes.

A. OBJECTIVES AND SCOPE

Innovative reactor concepts make use of passive safety features to a large extent in combination with active safety or operational systems. Following the IAEA definitions, a passive system does not need external input (especially energy) to operate. This is why it is expected that passive systems combine among others the advantages of simplicity, reduction of the need for human interaction, reduction or avoidance of external electrical power or signals.

Passive B systems (i.e. implementing moving working fluid, following IAEA classification [1]) that we will name also the thermal-hydraulic (T-H) passive systems, rely in these designs on natural forces, such as gravity or natural convection, to perform their accident prevention and mitigation functions once actuated and started. These driving forces are not generated by external power sources (e.g., pumped systems), as is the case in operating and evolutionary reactor designs. Because the magnitude of the natural forces, which drive the operation of passive systems, is relatively small, counter-forces (e.g., friction) can be of comparable magnitude and cannot be ignored as is usually done with pumped systems. Moreover, there are considerable uncertainties associated with factors on which the magnitude of these forces and counter forces depend (e.g., values of heat transfer coefficients and pressure losses). In addition, the magnitude of such natural driving forces depends on the specific plant conditions and configurations which could be existing at the time a system is called upon to perform its safety function. All these uncertainties affect the passive system thermal-hydraulic performances.

For all the reasons, it appeared necessary to create a specific methodology to assess the T-H passive system reliability. This methodology was to answer the following questions:

- How to identify and evaluate the sources of uncertainties and how to determine the important variables, i.e. those variables whose uncertainty has a significant impact on the T-H performance of passive systems?
- How to propagate efficiently the uncertainties through T-H codes and how to assess the unreliability of the T-H passive system?
- How to link in an accident sequence, the T-H passive system unreliability with other sources of unreliability (failure of active systems, human errors...) in order to evaluate the influence of the passive system on the sequence?

The methodology was to be tested on industrial examples of passive systems.

B. WORK PROGRAMME

The work content was structured following three main sub-objectives:

a) **Identification and quantification of the sources of uncertainties and determination of the important variables**

At this sub-objective corresponds the **Work Package 1 (WP1).** It is subdivided into three tasks.

WP1.1 treats the problem of identification and quantification of the sources of uncertainties in a model of T-H passive system. It will furnish a state-of-the-art on the available methods and a proposition of methodology.

WP1.2 concerns the methods for the determination of the important variables. It will furnish a state-of-the-art on the available methods and a proposition of methodology.

WP1.3 includes the choice and the definition of T-H passive systems that will be used as industrial study cases during the entire project. The methodologies proposed in WP1.1 and WP1.2 were to be tested on these industrial study cases.

WP1 was to furnish a coherent methodology based on expert judgement and statistical analysis.

b) **Propagation of the uncertainties through T-H models and evaluation of T-H passive system reliability**

At this sub-objective corresponds the **Work Package 2 (WP2).** It is subdivided into three tasks.

WP2.1 is a state-of-the-art on the methods for propagating the uncertainties through T-H models and for evaluating the reliability of a T-H passive system.

WP2.2 is a comparison of the methods identified in WP2.1 on the industrial study cases.

WP2.3 concerns the development of complementary methods, according to the results of WP2.2.

WP2 was to furnish a specific methodology for evaluating the reliability of T-H passive systems.

c) **Introduction of passive system unreliability in the accident sequence analysis**

At these sub-objectives corresponds the **Work Package 3 (WP3).** It is subdivided into three tasks.

WP3.1 is a state-of-the-art on possible approaches to introduce passive system T-H unreliability in accident sequence.

WP3.2 is a comparison of the possible approaches on the industrial study case and on a simplified scenario.

WP3.3 is a proposition for a specific methodology built up on the results of tasks WP3.1 and WP3.2.

WP3 was to furnish a state-of-the-art and a proposition for developing a specific methodology.

The project had to produce **a final report** based on the results of the three work-packages presenting the final methodology adopted and where the main results obtained in the frame of this work on the industrial study cases were to be underlined.

The development and implementation of a new methodology for evaluating the relative contribution of a T-H passive system to the total risk of failure in an accidental sequence and more quantitative evaluation was outside the scope of this project. However, the results of this project were to provide a sound technical basis and a guidance which should allow to achieve such a goal in a further step.

Since the 1st January 2003, a new partner "Technical University of Sofia-Research and Development Sector" (TUS-RDS) (Bulgaria) participated to the project in the framework of a NAS extension of the RMPS project.

This extension included a modification of the existing work-packages with the objective that TUS-RDS participates to the development of the methodology and a new work package (**WP4**) was created for the specific application of the methodology to the VVER reactors.

The Gantt Chart of RMPS including the NAS extension is given in Figure 1.

C. WORK PERFORMED AND RESULTS

C.1 INTRODUCTION

The objective of the project is to propose a specific methodology to evaluate the reliability of a thermal-hydraulic (T-H) passive system and to integrate this reliability in accidental sequence of Probabilistic Safety Analysis.

The paragraph C.2 presents an overview of the methodology used to evaluate the reliability of a passive system once given the characteristics of the accidental scenario. This methodology treats the problems of **identification and quantification of the sources of uncertainties and determination of the important variables (WP1)** and **propagation of the uncertainties through T-H models and evaluation of T-H passive system reliability (WP2)**

This chapter contains a nomenclature of the main terms used within the project and a roadmap of the methodology. Each step of the methodology is then clarified.

The paragraph C.3 concerns the specific point of the **integration of passive system reliability in Probabilistic Safety Assessment** and corresponds to **WP3**.

As foreseen in the four work-packages, the methodology has been tested on examples of industrial T-H passive systems. Three examples of passive systems have been treated within the framework of the RMPS project:

- the Isolation Condenser System (ICS) of BWR reactors,
- the Residual Passive heat Removal system on Primary circuit (RP2) of PWR reactors,
- The Hydro-Accumulator (HA) system of PWR, VVER type reactors.

The chapter C.4 presents the main results obtained on these examples. The three examples are used to test the points of the methodology corresponding to WP1 and WP2. The second example has been used to test the integration of passive system reliability in Probabilistic Safety Assessment (WP3). The last example corresponds more precisely to WP4.

C.2 METHODOLOGY OVERVIEW

The methodology proposed foresees several steps, which are depicted in Fig.2 and are detailed in the following paragraphs. This roadmap does not include the part corresponding to the integration of the passive system reliability in accidental sequences which is presented in the paragraph C.3.

C.2.1 Definition of the accidental scenario

The first step of the methodology is the definition of the accidental scenario in which the system will operate. The knowledge of this scenario will allow the specific definition of failure criteria and relevant parameters and the specific quantification of the uncertainties. On the other hand, the results obtained in the reliability and sensitivity analyses of the system will be specific to this scenario. A global evaluation of the system could be obtained by the integration of the system reliability in a Probabilistic Safety Assessment in which all the sequences involving the passive system will be considered. Another possibility can be the evaluation of the system reliability for the worse scenario considered or to take large ranges of variation of the uncertain parameters in order to take into account the larger variability covering all the scenarios involving the system.

C.2.2 Characterisation of the system

The goal of this analysis is to obtain information about the passive system behaviour, in an accident occurring during the life of the nuclear reactor and to identify the failure zones and conditions, if they exist. For that, we have to define the missions of the system, its failure modes and the failure criteria.

C.2.2.1 Mission of the system

The missions of the system are the goals for which the Passive System has been designed and located within the complete system. For instance, the mission of the passive system can be the decay heat removal, the cooling of the vessel, the pressure decrease of the primary circuit… In some case, the passive system can be designed to fulfil several missions in the same time or different missions depending on the considered scenario.

C.2.2.2 Failure mode

Due to the complexity of thermal-hydraulic phenomena and to the interaction between the passive system and the complete system, it is not always obvious to associate a failure mode to a mission of the system.

A qualitative analysis [Del1] is often necessary in order to identify potential failure modes and their consequences associated with the passive system operation. The aim of this analysis is to identify the parameters judged critical for the passive system performance allowing the association between failure modes and corresponding indicators of the failure cause. The methodology can be combined with a hazard identification qualitative method as FMEA (Failure Mode and Effect Analysis). During the process of characterisation, modelling and evaluation of the passive system, new failure modes can be identified (such as flow oscillations, plugs phenomena due to non-condensable gases…) which also have be taken into account.

C.2.2.3 Success/failure criteria

The knowledge of the system missions and failure modes allows the evaluation of the failure criteria. The failure criteria can be established as single-targets (e.g. the system must deliver a specific quantity of liquid within a fixed time) or as a function of time targets or integral values over a mission time (e.g. the system must reject at least a mean value of thermal power all along the system intervention). In some cases, it can be better to define a global failure criterion of the complete system instead of a specific criterion concerning the passive system. For instance the failure criterion can be based on the maximal clad temperature during a specified period. In this case, it is necessary to have modelled the complete system and not only the passive system.

C.2.3 Modelling of the system

Due to the lack of suitable experimental databases for passive systems in operation, the evaluation should rely on numerical modelling, e.g. by means of simulation via best-estimate codes. The system analysis should be carried out with a qualified thermal-hydraulic system code and performing best estimate calculations. Indeed there is an increasing interest in computational reactor safety analysis to replace the conservative evaluation model calculations by best estimate calculations supplemented by a quantitative uncertainty analysis. Specially in the present methodology where the objective is the evaluation of the reliability of the passive system, it is important to calculate the passive system performance in a realistic and not in a conservative way.

C.2.4 Identification of the sources of uncertainties

First of all, the method requires the identification of the potentially important contributors to uncertainty of the code results. These contributors consist of

- Approximations in modelling the physical processes : for instance the treatment of a liquid steam mixture as an homogeneous fluid, the use of empirical correlation...
- Approximations in modelling the system geometry : simplification of complex geometry features and approximation of a three-dimensional system.
- The input variables: initial and boundary conditions, such as plant temperatures, pressures, water levels and reactor power, dimensions, physical properties, such as densities, conductivities, specific heats, and thermal-hydraulic parameters, such as heat transfer coefficients or friction factors.

This identification of the relevant parameters must be based on the Expert Opinion of the physical process and of the thermal hydraulic codes.

Various methodologies have been developed in order to evaluate the overall uncertainty in the physical model predictions and some efforts have been made aimed at the internal assessment of uncertainty capability for thermal hydraulic codes [2]. However, in the present study, the uncertainties pertaining to the code are not accounted for, focusing the attention on the uncertainties relative to the input parameters of the code, characteristic of the passive system or of the complete system.

C.2.5 Identification of the relevant parameters

Among all the sources of uncertainties, The evaluation of the reliability of a passive system requires the identification of the relevant parameters which really affect the accomplishment of the target of the system. The tool here chosen for this task is the **Analytic Hierarchy Process** [3], which provides a qualitative and schematic, but rigorous and transparent, method to model the process under investigation. This method is composed of three major steps: the building of a hierarchy to decompose the problem at hand, the input of pairwise comparison judgments regarding the relevance of the considered parameters and the computation of priority vectors to obtain their ranking. The method is intended, in our case, to provide a transparent method to model the thermal-hydraulic process of the passive system under investigation, so as to allow selecting the important parameters related to the target of the system design.

C.2.6 Quantification of the uncertainties

A key issue in this process is the selection of the distributions for the input parameters. This is based on the experience from validation of the computer code by comparison between model predictions and test data of integral tests and separate effects tests for the model parameters as well as on known measurement uncertainties. The main objective is that the selected distribution for each input parameter must quantify the analyst’s state of knowledge for that parameter and express the reliable and available information about the parameter. The choice of distribution may highly affect the passive system reliability evaluations.

Different points of view have to be considered for this quantification:

- The amount of data:

When the data on a parameter are abundant, we can use statistical methods such as maximum likelihood method or method of moments to adjust analytical Density Functions and we can use different goodness-of-fit tests (Chi square, Kolmogorov…) to find the best analytical fit to the data. When the data are sparse or non-existent and this is generally the case when we consider the uncertainties affecting the passive system performance, the evaluation of the probability functions of the uncertain parameters must be based on the expert judgments. These distributions are quantitative expressions of the state of knowledge and can be modified if there is new evidence. If suitable observations become available, they can be used consistently to update the distributions.

- The dependence between the parameters:

If parameters have contributors to their uncertainty in common, the respective states of knowledge are dependent. As a consequence of this dependence, parameter values can not be combined freely and independently. Instances of such limitations need to be identified and the dependencies need to be quantified, if judged to be potentially important. If the analyst knows of dependencies between parameters explicitly, multivariate distributions or conditional subjective probability distribution function (pdf) may be used. The dependence between the parameters can be also introduced by covariance matrices or by functional relations between the parameters.

C.2.7 Sensitivity analysis

C.2.7.1 Objectives

An important feature of the methodology is to evaluate sensitivity measures of the importance of parameter uncertainties on the uncertainty of the passive system performance. These sensitivity measures give a ranking of input parameters. This information provides guidance as to where to improve the state of knowledge in order to reduce the output uncertainties most effectively. If experimental results are available to compare with calculations, sensitivity measures provide guidance where to improve the models of the computer code.

A state of the art has been carried out and is presented in [Del2]. We can summarize it as follows. Sometimes the lack of operational experience and significant data concerning the passive system performance forces the analysis to be performed in a **qualitative** way aimed at identifying for each failure mode, both the level of uncertainty associated with the phenomenon and the sensitivity of failure probability to that phenomenon [Del2]. The **quantitative** sensitivity analysis is performed by T-H calculations. It consists in ranking the parameters according to their relative contribution on the whole code response uncertainty and quantifying this contribution for each parameter. To apportion the variation in the output to the different parameters, many techniques could be used [4], each yielding different measures of sensitivity. An usual approach is to base the sensitivity analysis on a linear regression method, which is based on the hypothesis of a **linear** relation between response and input parameters. This, in case of passive systems is often restrictive. However, the method is simple and quick, and provides useful insights in case of a restricted number of sampling, as will be our case. Three different sensitivity coefficients have been considered, each one providing a slightly different information on the relevance of a parameter: Standardized Regression Coefficients (SRC), Partial Correlation Coefficients (PCC) and Correlation Coefficients (CC). These coefficients are described in [4] and [Del2]. Small differences between the different coefficients may be due to a certain degree of correlation between the inputs and to the system non-linearity. These occurrences should be analysed, the first one possibly through the examination of the correlation matrix and the second one calculating the determination coefficient of the model R^2 for example. Depending on the nature of the model representing the passive system operation and giving its performances, it can be more accurate to use sensitivity methods developed for non-monotonous or non linear models. In case **of non-linear but monotonous models**, we can perform rank transformations and calculate associated indices: standardized rank regression coefficients (SRRCs) and partial rank correlation coefficients (PRCCs) [4, Del2]. The rank transform is a simple procedure, which involves replacing the data with their corresponding ranks. We can also calculate a coefficient of determination based on the rank R^{2*}. The R^{2*} will be higher than the R^2 in case of non-linear models. The difference between R^2 and R^{2*} is a useful indicator of nonlinearity of the model. For **non linear and non monotonous models**, two methods exist: the Fourier Amplitude Sensitivity Test (FAST) and the Sobol method [4, Del2]. The general idea of these methods is to decompose the total variance of the response, in terms corresponding to part of the variance coming from the uncertainty on the input parameters taken independently, in terms corresponding to the interaction between two parameters, in terms corresponding to the interaction between three parameters, etc. The Sobol indices are calculated by Monte-Carlo simulation. The problem of these methods, and specially Sobol method, is that a good estimation of these indices requires a great number of calculations. (i.e. 10000 simulations). Thus it is often necessary first to calculate a response surface validated in the domain of variation of the random variables.

C.2.8 Reliability evaluations

Different methods can be used to quantify the reliability of the passive system once given a best estimate T-H code and a model of the system. These methods have been described in details in [Del4] with theirs advantages and drawbacks. We give here a summary of this state of the art.

The performance function of a passive system according to a specified mission is given by:

$$M = performance\ criterion - \ limit = g(X_1, X_2, ..., X_n)$$

in which the X_i $(i=1,...,n)$ are the n basic random variables (input parameters), and $g(.)$ is the functional relationship between the random variables and the failure of the system. The performance function can be defined such that the limit state, or failure surface, is given by $M = 0$. The failure event is defined as the space where $M < 0$, and the success event is defined as the space where $M > 0$. Thus a probability of failure can be evaluated by the following integral:

$$P_f = \int\int ... \int f_X(x_1, x_2, ..., x_n)\, dx_1, dx_2, ..., dx_n \qquad (1)$$

where f_X is the joint density function of $X_1, X_2, ..., X_n$, and the integration is performed over the region where $M < 0$. Because each of the basic random variables has a unique distribution and they interact, the integral (1) cannot be easily evaluated. Two types of methods can be used to estimate the probability of failure: the Monte Carlo simulation with or without variance reduction techniques and the approximated methods (FORM/SORM).

C.2.8.1 Reliability evaluations using Monte-Carlo simulation

Direct Monte-Carlo simulation techniques [5,6] can be used to estimate the probability of failure defined in Eq. (1) (or its complement to 1, the reliability). Monte-Carlo simulation consists of drawing samples of the basic variables according to their probabilistic characteristics and then feeding then into the performance function. An estimate $\overline{P_f}$ of the probability of failure P_f can be found in dividing the number of simulation cycles in which $g(.) < 0$, by the total number of simulation cycles N. As N approaches infinity, $\overline{P_f}$ approaches the true probability of failure. The accuracy of the estimation can be evaluated in terms of its variance and it is recommended to measure the statistical accuracy of the estimated probability of failure by computing its coefficient of variation The smaller the coefficient of variation, the better the accuracy of the estimated probability of failure. For a small probability of failure and a small number of simulation cycles, the variance of $\overline{P_f}$ can be quite large. Consequently, it may take a large number of simulation cycles to achieve a specific accuracy. The amount of computer time needed for the direct Monte Carlo method is large, specially in our case where each simulation cycle involves a long calculation (several hours) performed by a thermal-hydraulic code.

Variance reduction techniques offer an increase in the efficiency and the accuracy of the failure probability assessment in comparison with Direct Monte-Carlo simulation, for a same number of runs. In [Del4], we have presented various variance reduction techniques: Importance sampling, Stratified sampling, Latin hypercube sampling and Directional simulation. Latin hypercube sampling is one of the most efficient method for the propagation of the uncertainty, but it is generally not efficient for the assessment of small probability.

C.2.8.2 Approximated methods (FORM/SORM)

The first- and second-order reliability methods (FORM/SORM) consist of 4 steps [7,8]:

1. the transformation of the space of the basic random variables $X_1, X_2,...,X_n$ into a space of standard normal variables,
2. the research, in this transformed space, of the point of minimum distance from the origin on the limit state surface (this point is called the design point),
3. an approximation of the failure surface near the design point,
4. a computation of the failure probability corresponding to the approximating failure surface.

FORM and SORM apply only to problems where the set of basic variables are continuous. For small order probabilities, FORM/SORM are extremely efficient as compared to simulation methods. The calculation time is for FORM approximately linear in the number of basic variables and independent of the probability level. The drawback of these methods is when the failure surface is not sufficiently smooth, problems arise in the research of the design point.

C.2.8.3 Response Surface Methods

In a passive system, a large number of variables influences the performance of the system. Suppose performance criterion Y depends on the inputs variables $X_1, X_2,...,X_n$. Experiments are conducted with design variables $X_1, X_2,...,X_n$ a sufficient number of times to define the response surface to the level of accuracy desired. Each experiment can be represented by a point with coordinates $x_{1j}, x_{2j},...,x_{nj}$ in an n-dimensional space. The basic response procedure is to approximate $g(X)$ by a simple mathematical function (e.g. a n^{th} order polynomial) $\tilde{g}(X)$ with undetermined coefficients. Thermal-hydraulic analysis is performed at various points x_i, in order to determine the unknown coefficients in the polynomial $\tilde{g}(X)$ such that the error is minimum in the region of interest. When a response surface has been determined, the passive system reliability can be easily assessed in using Monte Carlo simulation. In [Del4], we have presented some techniques to fit response surface and some experimental designs to choose the experimental points. In [Del6], we have described a method to build and validate response surfaces. On various examples, we have shown the capabilities of neural network response surfaces [9] to simulate a discontinuous phenomena with regard to uncertainty, sensitivity and reliability studies and how to use bootstrap method [10] in combination with uncertainty and sensitivity computation to validate a response surface.

C.2.8.4 Influence of choices of the input distribution on the output

The codes used to calculate the T-H performance of the passive systems may require several hours for each run. The evaluation of the reliability of the passive system may require hundreds of calculation. This fact makes almost impossible to run again the code hundreds of time to estimate the effect of changes in the probabilistic distributions of the input parameters on the system reliability. In [Del6], we have assessed two methods to measure the influence of input distribution changes in the means and the distribution functions of the output variables, without running again the T-H code: the weighting and the rejection methods [11,12]. These methods were tested on an example of passive system.

C.3 INTEGRATION OF PASSIVE SYSTEM RELIABILITY IN PSA

The objective of this part of the methodology is the development of a consistent approach for introducing passive system reliability in an accident sequence of Probabilistic Safety Assessments (PSA). The treatment of passive systems in PSA models is a difficult and challenging task. No commonly accepted practices exist so far on how reliability of passive systems can be taken into account. The main challenge arises from the nature of passive systems which main operating principles are based not on active components, but on physical phenomena. In [Del7], we have presented a short state of the art of the Probabilistic Safety Assessment (PSA) including considerations on the way to incorporate the physical uncertainties on the passive system in an accident sequence.

This state of the art and first considerations have been followed by the treatment of an example in order to test the possibilities to integrate passive system reliability in a PSA sequence. In a first approach, applied to a simplified PSA carried out on a fictitious reactor equipped with two types of safety passive systems [Del8], we have chosen an Event Tree (ET) representation of the accidental scenario. ET techniques allows identifying all the different chains of accident sequences deriving from the initiating events. ET development implies each sequence represents a certain combination of events, corresponding to failed or operating safety or front-line systems: thus ETs, starting from the initiators, branch down following success or failure of the mitigating features, that match the ET headings, therefore providing a set of alternative consequences. The failures analyses performed on this reactor have allowed the characterisation of the technical failures (on valves, tubes in exchanger and safety injection check valves) and the ranges of variation of uncertain parameters which influence the physical process. The majority of the sequences of this event tree have been analysed by deterministic evaluations with envelope values of the uncertain parameters. For some sequences where the definition of envelope cases was impossible, basic events corresponding to the failure of the physical process have been added and uncertainty analyses have been performed to evaluate the corresponding probability of failure. For this purpose, the thermal-hydraulic code has been coupled to a Monte-Carlo simulation module. The failure probabilities obtained by these reliability analyses have been integrated in the corresponding sequences. This methodology allows the probabilistic evaluation of the influence of the passive system on an accidental scenario and could be used to test the interest to replace an active system by a passive system on specific situations. All the results of this exercise are presented in [Del8] and are summarised in paragraph C.4.2.7.

Finally in [Del9], we have proposed recommendations, based on the results obtained on the previous example, on the ways to integrate a passive system in a PSA sequence and guidelines for the development of complementary methods. The discussion about the incorporation of passive systems within an accident sequence in the fashion of a front-line system, within a PSA framework, highlighted the need for the development of dynamic event trees, as compared to conventional PSAs which do not systematically model the dynamic aspects of accident progression, including dynamic system interactions and dependencies and thermal hydraulic phenomena induced failures. This requirement emerges from the consideration that thermal hydraulic natural circulation passive system operation is strongly dependent, more than other safety systems, on the state/parameter evolution of the system during the accident progression.

C.4 MAIN RESULTS OBTAINED ON THE EXAMPLES OF PASSIVE SYSTEMS

Three examples of passive systems have been treated within the framework of the RMPS project:

- the Isolation Condenser System (ICS) of BWR reactors,
- the Residual Passive heat Removal system on Primary circuit (RP2) of PWR reactors,
- The Hydro-Accumulator (HA) system of PWR, VVER type reactors.

We present her the main results obtained on these examples.

C.4.1 Isolation condenser system

The complete results concerning this example have been presented in [Del3,Del5].

C.4.1.1 IC system description

The aim of the ICS is the decay heat removal during accidental operation using passive function. The system is presented in fig. 3. A pipe, which is connected to the reactor pressure vessel (RPV), in BWR type application (or to the Steam Generator of the PWRs), is used to direct the steam to a heat exchanger, which is immersed in a cooling pool. In every configuration, the pool is placed higher than the element to be cooled (vessel or steam generator) in order to ensure a flow in natural convection, which guarantees a minimum of human of mechanical interventions. The steam side connection between the vessel and the IC is normally open and the condensate line is normally closed. This allows the isolation condenser and drain piping to fill with condensate, which is maintained at a sub-cooled temperature by the pool water during normal reactor operation. The IC is started into operation, after opening a valve, by draining the condensate to the reactor, thus causing steam from the reactor to fill the tubes, which transfer heat to the cooler pool water.

C.4.1.2 Modelling by thermal-hydraulic codes

The Isolation Condenser modelling is derived from the IC experimental programme performed at the PANDA facility (Paul Scherrer Institute in Switzerland). Relevant dimensions and the ‘nominal/design’ operating conditions were taken from the Panda project and from SBWR design. As in the experimental program, only the RPV and the IC system are modelled. The conditions of the complete reactor are represented by the pressure and the level in the RPV. The transient operation starts with the opening of the valve. The IC system has been modelled separately by ATHLET, RELAP5 (mod3.1 and mod 3.2) and CATHARE. Comparisons have been carried out between the codes on the following parameters : vessel pressure, liquids levels for the RPV, the IC pool and the IC tubes primary side, the fluid temperatures for the pool and inside of condenser tubes, the thermal power exchanged across the IC and the mass flow rate at IC outlet. Globally a good agreement between the codes has been obtained on the reference case in taking the nominal conditions.

C.4.1.3 Application of the Analytical Hierarchy Process for the identification of the relevant parameters

To perform the AHP, an actual elicitation of pairwise comparisons from five experts has been carried out in two successive phases [15]. The results of the a priori AHP were compared to those of the sensitivity analysis on the previously selected parameters (Table 1). It turns out that the rankings resulting from the two approaches are quite different, albeit in some cases similar, since many of the parameters which turned out to be important from the Sensitivity Analysis performed, were on average considered less important than others by the five experts involved in the AHP. Thus, the analysis has been proved to be useful a posteriori to review the work done, and a priori to systematically guide the selection of the relevant parameters for the best-estimate code runs of the passive system reliability assessment. The method has proved to be transparent and easy to handle, fast and flexible. Finally, although here the method has been applied for assessing the reliability of an existing thermal hydraulic passive system of reference, it could be used also to estimate the influences of parameters during the design phase of new projects.

C.4.1.4 Identification of the sources of uncertainties

Once defined the mission of the system, i.e. the rejection of the core decay power to an external heat sink in this case study, a series of discussions on the main phenomena involved in the physical behaviour of the passive system has been carried out. That led to the identification of those quantities having the capability to degrade, to hamper or to prevent the fulfilment of the mission.

Two categories of parameters have been defined: the design and the critical categories [13]. The **design parameters** refer to the quantities directly connected to the design of the system, to the quantities representing the physical links of the passive system to the whole system into which it is inserted (e.g. the primary system), and to the parameters identifying the status or behaviour of the passive system during its functioning, in nominal or operational conditions. The **critical parameters** refer to the quantities that could represent a direct "source of failure" for the passive system, i.e. they could leave the mission unfulfilled. Therefore the critical parameters are directly connected to the physical phenomenology involved in the passive system behaviour that could impair it. In practice, the design and critical parameters refer to initial conditions and boundary conditions for the Passive System, thus identifying a specific configuration of the system, at the beginning and all along the mission time.

C.4.1.5 Range of variation and probabilistic representation of the random variables

A range of variation and a probability density function have been assigned to each uncertain parameter. This probabilistic quantification has been performed via a sort of rough, unstructured "expert" or "engineering" judgment procedure. In order to simplify both the identification of the ranges and their corresponding probabilities, discrete values have been selected. As a general rule, a central pivot has been identified, and then the range has been extended to higher and lower values, if applicable. The pivot value represents the nominal condition for the parameter. The limits have been chosen in order to exclude unrealistic values or those values representing a limit zone for the operation demand of the passive system. Once the discrete ranges have been set up, discrete probability distributions have been associated. The reasons for the selection of the parameters, with their ranges and probability distributions, have been justified in [Del3]. The table 2 gives the uncertain parameters with their discrete probability distributions.

In order to perform complementary uncertainty analysis and unreliability assessment of the ICS system and to avoid problems linked to the use of discrete distributions, it was decided to define continuous probability density functions (*pdf*) built on the basis of the discrete distributions. The arbitrariness has been pointed out to translate a discrete distribution to a continuous one, if the probabilities are given for discrete values and not for discrete intervals. In a consequence, the probabilities corresponding to given intervals must be asked to the experts instead of the probabilities for given values.

C.4.1.6 Failure criteria and indicators of system performance

Acceptability or design limits for the system operation must be known in order to assign failure criteria and to define indicators of system performance. Those limits are specific for the system and connected with its mission. Several acceptability limits and even a larger number of failure criteria can be identified. A systematic evaluation of acceptability limits and of failure criteria does not constitute the purpose of the present activity. However, parameters connected with acceptability or design limits are selected and failure criteria are defined as a consequence.

The thermal power exchanged across the IC (W) appeared to be the output parameter of the reference code the most connected with the acceptability or design limits of the system. The ratio Y/Y_{ref}, where Y is the integral of W on the transient and suffix *ref* indicates the nominal reference case, was chosen as "performance criterion" of the system.

C.4.1.7 Thermal-Hydraulic calculations

Different selections of the uncertain parameters have been considered: deterministic selection, statistic selection in taking into account the discrete probability density functions (*pdf*) and statistic selection in taking into account the continue *pdf* extrapolated from the discrete *pd*f.

With the RELAP5 code, 144 code runs (6 deterministic + 69 with discrete *pdf* + 69 with continuous *pdf*) were performed both with the versions 3.1 and 3.2. With the CATHARE code (version 1.5a mod. 3.1), 75 code runs (6 deterministic + 69 with discrete *pdf*) were performed. With ATHLET, 69 code runs (with discrete *pdf*) were performed. Figure 4 compares the relative differences on the performance criterion obtained by the codes with reference to RELAP/mod3.2 on 75 code runs (6 deterministic + 69 with discrete *pdf*). From these comparisons, we can notice a good overall agreement between the results of the codes, with some differences: RELAP5/mod3.1 provides in general the largest amount of exchanged power and RELAP5/mod3.2 the lowest. Between these two bounds, CATHARE calculates in general larger amount of exchanged power than ATHLET. These results are coherent with the observations made on the reference case. The scattering on the relative difference is around 60% if we consider the four codes. The results of ATHLET are more scattered. The scattering on the relative difference is around 40% if we consider only CATHARE and RELAP5/mod3.1 and mod3.2.

C.4.1.8 Sensitivity analysis

The importance of input variables on the transient evolution has been analysed by performing a sensitivity analysis under the hypothesis of linearity between the input and the output variables. Different coefficients of importance: Standardized Regression Coefficients (SRC) and Partial correlation coefficients (PCC), Standardized rank regression coefficients (SRRC) and Partial rank correlation coefficients (PRCC), have been calculated for each parameter, and a coherent general ranking was assessed. The results show that the reactor vessel pressure and the non-condensable fraction in the RPV are the most important parameters for the passive system behaviour. The results of the sensitivity analyses obtained by RELAP and CATHARE have been compared and good accordance was found. The behaviour of this criterion with respect to the input parameters is however more linear on the results obtained by CATHARE than on those of RELAP. Figure 5 presents the results obtained on the CATHARE calculations. The hypothesis of linearity may not always apply so that a non linear analysis tool should be used to obtain more realistic results. The degree of correlation between input parameters should also be taken in account. A non-linear analysis has been performed on the CATHARE results in using the Sobol indices. The result of this analysis shows that the reactor vessel non-condensable fraction is the most important parameter.

C.4.1.9 Reliability of the system

Different proposals have been made to represent the reliability of the system. The first proposal consists in a sort of *scatter data plot* representation where the code evaluations (runs) are displayed in terms of the probability of occurrence of that boundary and initial conditions versus the defined performance criterion. This kind of representation has more similarity with the classical representation of risk results in terms of probability vs. consequence. The system reliability could then be evaluated with respect to the selected failure criteria. A failure zone could be defined and the reliability of the system could be represented by the sum of the probabilities of the runs in the non-failure domain. In principle, a probability function (*pdf*) curve for the passive system mission can be obtained. The second proposal, more classical and which obtained the consensus of all partners, consists in fitting the **density function** of the performance criterion on the results of the runs. The *pdf* can be fitted on the empirical histogram of the criterion (or the cumulative density function on the empirical cumulative distribution) by moment or maximum likelihood methods. Different tests exist to evaluate the quality of the fitting (Chi-2, Kolmogorov, …). The knowledge of the *pdf* facilitates the unreliability calculation.

For the reliability evaluation, 92 calculations were performed with CATHARE in considering discrete probability distributions for the 11 input parameters considered as uncertain. To avoid the problem of long computer time in the method of Monte-Carlo, approximate mathematical models called response surfaces have been built on the results of the 92 calculations. Different types of response surfaces have been fitted on the 92 results obtained by CATHARE: linear, non linear and Neural Network (NN) response surfaces. The best fit based on the coefficient of determination R^2 was obtained for the NN response surfaces. For the reliability evaluation of the ICS, we have defined a failure criterion consisting in the comparison of the thermal power ratio to a given limit α. The mission of the system is supposed fulfilled if the thermal power ratio is greater or equal the limit α, or in other words if the system has sufficiently exchanged heat to assure a sufficient decay heat removal during the accidental transient. The limit α has not yet been fixed for the ICS and it is beyond the purpose of the present project to supply this limit. We can imagine that this limit could be fixed by the Safety Authorities and could be different with regard to the mission given to the system. So in order to perform reliability evaluation of the system, we have performed different calculations in considering different values of the limit α. The failure probabilities have been obtained in using the non linear responses surface and the NN response surface and in performing 10000 Monte Carlo runs

In order to use FORM /SORM methods for the evaluation of the reliability of the ICS system, it was necessary to adjust analytical continuous probabilistic models to the 11 random variables. The results obtained by the FORM method are close to the results of the Monte-Carlo simulations, when both used the same input continuous analytical distributions. The knowledge of the design point allows the determination of the most influential variables on reliability. The figure 6 presents the evolution of the factors of sensitivity with respect to the criterion limit α. We can observe an increase in the importance of the variable P1 (vessel pressure) with α and a corresponding decrease of X_1 (non-condensable fraction in the pressure vessel). A positive value for the α_i indicates that an increase of the corresponding variable X_i leads to an increase of the failure probability and a negative value that an increase of the corresponding variable leads to an decrease of the failure probability.

In this example, only the passive system and the reactor pressure vessel have been modelled. The boundaries conditions of the passive system are represented by the pressure and the level in the RPV. This assumption will not allow to take into account possible coupling effects with other systems in the reactor. The reliability analysis has been carried out in considering broad ranges of variation for the characteristic parameters. These ranges were supposed to represent the whole set of initial configurations to which the system could be subjected without reference to a specific accident scenario. The advantage of this assumption is that it is possible to perform a single reliability analysis of the system and in this way to limit the number of thermal-hydraulic calculations. The drawback is that this single analysis could lead to conservative and not realistic results on the reliability of the passive system. For these reasons, it has been decided to treat another example, where the complete system will be modelled and where specific analyses for different scenarios will be carried out.

C.4.2 Residual Passive heat Removal system on the Primary circuit (RP2)

The complete results obtained on this example have been presented in [Del5,Del8].

C.4.2.1 Description of the RP2 system

The Residual Passive heat Removal system on the Primary circuit (RP2) system is composed of three circuits dedicated to the heat removal, each one being connected on a loop of the primary circuit (Fig. 7) [14]. Each circuit includes an exchanger immersed in a cooling pool located inside the containment, and a valve to allow its starting. For the study in progress, this valve was put on the cold leg of the system, downstream the exchanger. The exchanger is located higher than the main piping of the primary circuit to allow a natural convection between the core and the exchanger. On criterion of emergency shutdown of the reactor, the valve opens and the natural convection starts. The residual power produced by the fuel is transferred to the cooling pool via the RP2 exchanger. This system is quite similar to the PHRS from AP600, but its missions are different. AP600 only rely upon passive systems for Design Basis Accidents. RP2 has been designed within the framework of a new management principle, termed “Base Operation Passive Heat Removal” (BOPHR), where the residual power is removed jointly by active and passive systems, immediately after emergency shutdown.

C.4.2.2 Accidental scenario/System mission/failure criterion

The transient of Total Loss of the Power Supplies (or Blackout) was selected as reference accident for the reliability evaluation of the system. The objective of the safety systems is to avoid the melting at high pressure. Thus the mission of the RP2 system is double, on the one hand to depressurise the primary circuit, and on the other hand to avoid the fusion of the core

For the exercise, the duration of accidental calculation was fixed arbitrarily to 12 hours, a relatively long time where no human intervention is simulated. The failure of the system is obtained if the maximum temperature of the clad or the temperature of the fluid at the core output go beyond respectively the values of 500°C and 450°C, in less than 12 hours.

C.4.2.3 Modelling of the system

A modelling with CATHARE (1.5a Mod 3.1) of a complete pressurized water reactor PWR 900 MWe with the 3 independently simulated primary/secondary loops has been carried out. Each loop is equipped with the BOPHR/RP2 system with its exchanger immersed in a pool. The 3 cooling pools are modelled independently. Each system RP2 is connected to a primary loop between the hot and cold legs. Steady state calculation consists in carrying out the regulations of the characteristic parameters retained in the study with their target values. Once the regulations finish (primary circuit flow rate in the loops, Steam Generator levels, pools levels and feedwater flow rate of the Steam Generators) and all the values of the uncertain parameters imposed, the transient can start with all the physical parameters with the desired values.

C.4.2.4 Identification of the sources of uncertainties:

A set of 24 parameters likely to be more or less uncertain at the time of the RP2 passive system start-up and influencing significantly the performances of the system was identified by expert judgment. These parameters are called hereafter the characteristic parameters and are listed below.

For each of the three BOPHR/RP2 systems (i = 1,3):

- I_i: instant of opening of the isolation valve of the RP2;
- X_i: rate of non-condensable gas at the inlet of the RP2 exchanger;
- L_i: initial pool level;
- T_i: initial temperature of the water of the pool;
- C_i: fouling of the tubes of RP2 exchanger;
- R_i: number of broken tubes of RP2 exchanger.

For the primary circuit:

- PUI: percentage of the nominal power of the core;
- PP: pressure in the pressurizer;
- ANS: decay of residual power according to the ANS law.

For the secondary circuit (i = 1,3):

- NGVi: real secondary level in the three steam generators.

C.4.2.5 Thermal-hydraulic calculations on reference case

A preliminary calculation was carried out with the nominal values of the characteristic parameters with only 2 RP2 available (in taking into account the single failure criterion). The calculated transient was satisfactory. The mission of the RP2 is completely fulfilled. At the end of the 12 hours (43200s), the primary circuit is depressurised, and the cooling of the core is assured. In addition, with an aim of testing the response of the CATHARE code for extreme values of the characteristic parameters, calculations were carried out in taking the minimal and maximal values of each parameter on theirs ranges of variation.

C.4.2.6 Reliability and Sensitivity analysis of the RP2 system

Global analyses

The first reliability and sensitivity analyses of the RP2 system have been carried out in considering broad ranges of variation for the characteristic parameters. These ranges were supposed to represent the whole set of initial configurations to which the system could be subjected. In a second step, we decided to suppress the possibility of tube rupture at the RP2 start-up. Indeed the possibility of tube rupture could be included in the failure of mechanical components of the system in a Probability Safety Assessment. In this case, we obtained 21 random variables. 85 samples of the 21 random variables have been generated and for each sample a CATHARE calculation has been performed. All these cases led to a success of the system mission considering the failure criterion. In order to analyse the performance of the system, we have calculated a performance ratio: ratio between the sum of the energy extracted by each RP2 during the transient (12 hours) and the energy produced by the core during the transient. To perform sensitivity analysis on the performance of the system, different types of response surfaces have been fitted between the 21 input parameters and the output value of the ratio calculated by CATHARE: polynomial response surfaces (up to 3rd degree) and responses surfaces obtained by Neural Network Two types of sensitivity analysis have been carried out: a sensitivity analysis with linear coefficients (Standardized Regression Coefficients) even if the model is not fully linear ($R^2 = 0.77$) and sensitivity analysis with SOBOL indices calculated in using the Neural Network response surface and in performing 10000 simulations of this surface (fig. 8). The results of the calculation of Standardised Regression Coefficients and SOBOL indices give both the same indications: the most important variables are *ANS*, the residual power decay which is mainly due to the state of the fuel in the core when the transient occurs and I_1, I_2, I_3, the instants of opening of the RP2 valves which govern directly the duration of the heat exchange time in the RP2's.

Specific analyses

In the framework of the integration of the system reliability in a PSA (see paragraph C.4.2.7 and [Del8]) and in order to test the influence of the passive system on different accidental situations, specific ranges of variation and specific probabilistic density functions of the characteristic parameters have been identified for the studied sequences. Specific reliability and sensitivity analyses have been carried out for these sequences. The majority of the sequences of the simplified event tree have been analysed by deterministic evaluations with envelope values of the uncertain parameters. For two sequences where the definition of envelope cases was impossible, basic events corresponding to the failure of the physical process have been added to the event tree and uncertainty analyses have been performed to evaluate the corresponding probability of failure. These sequences were: the sequence with 2 RP2 available and no broken tube and the sequence with 2 RP2 available and one broken tube. For the sequence with two RP2 available and no broken tube in the RP2 exchanger, the number of characteristic parameters was reduced to 14 (there is only two RP2 systems and the number of broken tubes and the valve failure are no more considered in the uncertainty analysis, but taken into account in the event tree of the PSA). In addition, a monitoring system was supposed to be implemented on the RP2 system, in order to verify continuously that the RP2 loops are available when they are actuated. This led to narrower ranges of variation for the levels and the temperatures of the two pools. The choice of the probabilistic model presented in table 3 was based on engineer judgment. The results of the sensitivity analysis performed in calculating the Standardized Regression Coefficient and the Partial Correlation Coefficient show that the more influential parameters on the performance ratio are L_1 and L_2 the initial pool levels and the *ANS* curve. The objective of the uncertainty calculations was to evaluate the probability p_1 corresponding to the failure of the thermal-hydraulic process, considered as a basic event in the event tree, when only two RP2 are available. We have carried out 76 calculations with CATHARE with values of the input variables randomly generated in considering this probabilistic model. Among these 76 calculations, we obtained 18 cases of failure, leading to a rough estimation of the failure probability p_1 to 0.24. This T-H failure probability of the passive system is conditional with respect to the sequence considered and has to be multiplied by the probabilities of all the basic events involved in the sequence in order to determine the failure probability of the sequence [Del8]. In the same way, we determine a T-H failure probability p_2 equal to 0.04 for the RP2 passive system in the sequence with 2 RP2 available and one broken tube.

C.4.2.7 Integration of the Reliability of RP2 Passive System in Probabilistic Safety Assessment

This study [Del8] consisted in:

- carrying out a global quantitative evaluation of the reliability of the RP2 passive system,

- including this evaluation in a simplified PSA of PWR reactor,
- carrying out calculations of a set of CATHARE transients,
- including the CATHARE results in the PSA,
- evaluating the yearly occurrence frequency of core damage for the reactor equipped with safety passive systems, in case of transient of Total Loss of the Power Supplies (or Blackout),
- identifying complementary CATHARE calculations to test and validate the methodology.

The reliability analysis of the RP2 passive system underlines the existence of two types of failures which could affect the system:

- Failures on passive system components, which lead, directly or indirectly, to the loss of the system.
- The occurrence of an initial configuration of the passive system, which is not standard and leads to the loss of the system, mainly because of thermal-hydraulic reasons. The non standard configuration of the passive system does not allow to guarantee the good working of the system in case of demand.

For this second type of failures, we can consider two possibilities:

- A monitoring system can detect, before the occurrence of the blackout, the existence of the non standard configuration of the passive system. It is also considered that, as soon as the non standard configuration is detected, the automatic safety systems or the operators shutdown the reactor in safety state (shutdown of the reactor by instruction). The occurrence of this type of configuration lies in the failure of monitoring systems.
- No monitoring system can detect, before the occurrence of the blackout, the existence of a non standard configuration of the passive system. It is not considered that operators shutdown the reactor in safety state. The occurrence of this type of configuration lies in the existence of a set of characteristic parameters, corresponding to an initial non standard configuration of the passive system.

Thus, the approach to define probability of malfunction is different, following the type of malfunction. The accidental transient of Total Loss of the Power supplies (reactor in full power) has been chosen, as it was the reference transient having been used for the dimensioning of the safety systems dedicated to residual power removal. The probability of occurrence of this initiating event is 10^{-5}/year. The analysis is carried out through the method of event tree, integrating the RP2 loops and the safety injection by accumulators. The event tree is presented on figure 9. In order to simplify the event tree representation, the different numbers of RP2 loops available are presented in the same event tree. The core damage frequency, after a blackout, is estimated at $7.5.10^{-8}$/year. This frequency corresponds to the sum of the probabilities of each accident sequence leading to the core melt in pressure for the transient of blackout. The main accident sequence (sequence 5) represents 96% of the core damage frequency. This sequence corresponds to a T-H process failure when 1 RP2 loop has failed. This frequency is at the limit of the acceptability, as it does not respect the probabilistic objectives 10^{-7}/year for all the transient families, which corresponds for a transient family to 10^{-8}/year.

This result does not affect the design of the RP2 system which is efficient to avoid the high pressure core melt. Currently, the T-H analyses underlined:

- The efficiency of the system when the 3 RP2 loops are well running,
- A T-H process failure of 0.24 if only 2 RP2 loops are well running.

As result of this exercise, we concluded that it would be desirable to re-examine the dimensioning of the RP2 system, in order to obtain a well-running process, when 1 RP2 loop is in failure. The probabilistic objective to reach is 0.03 for the T-H process failure in case of 2 RP2 loops available. This value would allow to reach a yearly core damage frequency of 10^{-8} regarding the high pressure core damage for the studied transient family (blackout). The RP2 passive system, dimensioned in this way, should allow to reach the probabilistic safety objectives for a reactor integrating passive safety systems. These results underline the importance to take into account the T-H process failure probability to evaluate the reliability of a safety passive system.

C.4.3 Hydro-accumulator VVER

This chapter presents the example of the Hydro-Accumulator (HA) passive systems that are used in the units 5 and 6 of the Kozloduy NPP equipped with VVER - 1000 type reactors. The description of the system and the complete results on this example have been presented in [Del5,Del10-11]

C.4.3.1 Description of the HA system

The passive injection system or Hydraulic Accumulators consists of four tanks, pipelines, and fittings and are divided into two independent channels (Fig. 10). Each channel has two tanks filled with boric water and nitrogen under pressure above the boric water. The system ensures feeding of boric water in the upper and lower plenum of the reactor. Each pipeline connecting the tanks with the reactor has two main steam valves and two reversed valves. When the reactor is at nominal power, the main steam valves are fully opened. At an accidental reduction of the pressure in the main loop, the reversed valves automatically open and water from the tanks enters the zone of the reactor core. When the water level reaches the border limit of 900 mm from the tank's height a signal for low water level closes the main steam valves averting full emptying of the boric water in the tanks. In the tank construction, there are heating appliances, which provide appointed temperature within the limits of 150°C in order to avert abrupt fall of the temperature in the reactor core.

C.4.3.2 Modelling of the system

A modelling with RELAP5/mod3.2 of a complete pressurized water reactor VVER-1000 with four HA was carried out, with the following special features:

- Primary side is presented with four different loops.
- The core region is subdivided into 3 parallel regions (channels): hot, average and bypass channel.
- Each part of them is axially divided into 10 parts.
- Hot rods are modelled in both hot and average channel.
- The downcomer region is separated into four regions, each region attached to one cold leg. Cross flow junctions allow azimuthal flow among the regions.
- The pressurizer is connected to loop No. 4 through the surge line and loop No. 1 through the spray line.
- The Counter Current Flow Limitation (CCFL) is modelled at the core upper plate and at the downcomer upper junction.

- The full Emergency Core Cooling System (ECCS) and its injecting points are modelled including High Pressure Injection System (HPIS), Low Pressure Injection System (LPIS) and HA as designed.
- The break is modelled in loop No. 2.
- The steam generator secondary side arrangement takes into consideration the tube bundle water regions, the volume including the water level above tubing, the steam generator collectors, the steam dome and the internal downcomer. The side volumes between the heat exchanger tubes and boiler walls are added to allow recirculation in the model. These downcomer volumes also enable circulation inside the tube bundle volumes and in the side regions. The junctions between the tube bundle volumes and side volumes are cross flow type.
- Steam generator tube bundle is represented as 5 stack volumes at the height (5 layers). Horizontal tube bundle is divided into 2 major parts (to account for hot and cold collector). Each of these parts is subdivided into 8 volumes at its length.
- The steam lines and main steam header are modelled according to their real layout.

C.4.3.3 Accidental scenario

The accident is a ***Guillotine Cold Leg Rupture***. The following sequence of automatic actions was used:

- Due to the fast primary pressure drop, Reactor Protection System is actuated after 0.4 s by signal “Primary Pressure P1 < 150 kg/cm^2”. After 4s, all control rods drop to the core bottom.
- Due to primary pressure drop, subcooling reaches $\Delta t_S < 10\ ^oC$ then:
  a. Containment Localizing Valves close;
  b. Make-up system stops;
  c. After 15s, the Main Coolant Pumps stop;
  d. Actuation of Automatic Step by Step Load and start of Spray System, LPIS and HPIS :
    - Spray System after $P_{containment} > 0{,}2$ kg/cm^2
    - LPIS after $P_1 < 26$ kg/cm^2
    - HPIS after $P_1 < 110$ kg/cm^2
- 15s after scram, Main Isolation Valves close.
- At primary pressure $P_1 = 60$ kg/cm^2, the four HA (1- 4) injection start.

C.4.3.4 Definition of the characteristic parameters

A set of 8 parameters likely to be more or less uncertain and influencing significantly the performances of the system was defined. One will call thereafter these parameters, the characteristic parameters. These parameters are as follows:

For HA system (i = 1, 4):

- L_i - initial HA level;
- P_i - HA pressure;
- T_i - initial HA temperature;

For the primary circuit:

- NR - core power;
- PP - primary pressure;

- ANS - decay heat according to the ANS law;
- PF - core power peaking factor;
- CDC - critical flow discharge coefficients.

Preliminary calculations have shown that only HA parameters and CDC value have a significant impact on system behaviour and HA performance. The characteristic parameters considered in this study with their definite ranges of variation are given in Table 4.

C.4.3.5 Criteria of success and termination of the calculations

For all cases, calculation is terminated when the core is quenched, i.e. the cladding temperature decreases to the value which corresponds to the saturation temperature. The cladding temperature is investigated for the time period: between 12 s and the end of calculation, and the maximum value is detected. If this temperature is less than 870 ^{o}C (failure criteria), calculation will be then considered to correspond to the case 'success' from the point of view of the HA system efficiency.

C.4.3.6 Sensitivity and reliability analyses of the HA system

In order to perform reliability evaluations of the system and sensitivity analyses, we have considered the characteristic parameters as random variables and we have performed calculations for the values of these parameters given in Table 5. The core parameters are taken at their maximum values as follows:

- Core power 102 %;
- Primary pressure-163 bar;
- Radial and axial core peaking factors;
- Decay heat- ANS79 +20 %.

In order to obtain the failure probability of the HA system depending from the chosen ranges of variation of the parameters, the following approach has been used:

- For each parameter and for the values defined in Table 4, determination of the relation between the cladding temperature obtained from the RELAP calculations and the parameters.
- Approximation of the predicted relation, with polynomial functions:
- Calculation of an error coefficient (Maximal experimental value/ Maximal approximated value) in order to cover also the maximal predicted value. This correction gives the possibility to estimate the maximal observed deviation from the experimental values in every point of the approximation. We assume error factor up to 1.1 as satisfying the approximation.
- Evaluation of the failure probability as: $\mathbf{P = M_f / N}$ where M_f is the number of the points from the approximation, corrected with the error factor, which are above the failure criterion, i.e. the points from the approximated and corrected cladding temperature above the maximal acceptable temperature of 870 ^{o}C, and N of all points of the approximation (N=100). The main idea here is to calculate the failure probability of the HA system depending from the variation of the chosen hydro accumulator's parameters.

Only for the parameter HA pressure in the area 30-40 bar, the HA failure probability P is greater than 0 and equal to 0.13. This result is valid only if we take the corrected approximation with the error coefficient. This correction gives the possibility to estimate the maximal observed deviation from the experimental values in every point of the approximation. All other parameters do not cause the violation of the failure criterion during their variations. In the case where several functions meet the failure criterion, we could use the methodology, including multifunctional approximation, to obtain the general failure probability.

CONCLUSION

The RMPS project has allowed the development of a specific methodology for the evaluation of the reliability of passive system and its integration into the probabilistic analyses of accidental sequences. The methodology obtained deals with the following problems:

- Identification and quantification of the sources of uncertainties and determination of the important variables.
- Propagation of the uncertainties through T-H models and assessment of T-H passive system unreliability.
- Introduction of passive system unreliability in the accident sequence analysis.

Each step of the methodology has been described and commented and a diagram of the methodology has been presented. This methodology has been tested on three examples of passive systems: the Isolation Condenser System (ICS) of Boiling Water Reactor, the Residual Passive heat Removal system on the Primary circuit (RP2) of Pressurized Water Reactor and the Hydro-Accumulator (HA) of VVER 1000 reactors. Thermal-hydraulic calculations have been carried out with different codes (RELAP, ATHLET and CATHARE), and various methods of sensitivity analysis and reliability evaluation have been tested.

The Analytical Hierarchy Process has been chosen for the identification of the relevant parameters which really affect the accomplishment of the system mission. The results obtained on the examples have shown the interest of sensitivity analysis for the determination, among the uncertain parameters, of the main contributors to the risk of failure of the passive system. They have shown also that it is possible to evaluate the reliability of the systems for specific situations, once the probability density functions of the input parameters are defined, in using Monte-Carlo or FORM method. The use of response surface methods where the physical model is approximated by a simpler mathematical model is often necessary in order to reduce the number of calculations with the physical model.

The possibilities to integrate passive system reliability in a PSA sequence have been tested on an example. In a first approach, applied to a simplified PSA carried out on a fictitious reactor equipped with two types of safety passive systems, we have chosen an Event Tree (ET) representation of the accidental scenario. This methodology allows the probabilistic evaluation of the influence of the passive system on an accidental scenario and could be used to test the interest to replace an active system by a passive system on specific situations.

The developed methodology participates to the safety assessment of reactors equipped with passive systems. The development and the validation of a methodology of reliability analysis relative to passive safety systems are preconditions to the implementation of such systems on a nuclear reactor. This methodology is required to gain the necessary confidence of:

- The designers who define the architecture of reactors and safety systems. Indeed, the designers will accept new safety systems only if these systems remain at reasonable costs and with same efficiencies in comparison with the existing safety systems,
- Regulatory authorities who will have to accept the implementation of such systems on a nuclear reactor.

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[Pap2] Marquès M., Pignatel J.F., D'Auria F., Burgazzi L., Müller C., Bolado-Lavin R., Kirchsteiger C., La Lumia V., Ivanov I., Kalchev B., Reliability Methods for Passive Systems. Proceedings of ICAPP '04. Pittsburgh, PA USA, June 13-17, 2004.

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Deliverables RMPS

[Del1] Methods of identification and quantification of the sources of uncertainties. **Deliverable 1** of RMPS project. EVOL-RMPS-D01. April 2002.

[Del2] Methods of determination of the important variables. **Deliverable 2** of RMPS project. EVOL-RMPS-D02. April 2002.

[Del3] Industrial Study Case, part 1. **Deliverable 3** of RMPS project. EVOL-RMPS-D03. February 2003.

[Del4] Support Methods for estimating the Reliability of Passive Systems. **Deliverable 4** of RMPS project. EVOL-RMPS-D04. October 2002.

[Del5] Industrial Study Case, part 2. **Deliverable 5** of RMPS project. EVOL-RMPS-D05. April 2003.

[Del6] Development of complementary methods. **Deliverable 6** of RMPS project. EVOL-RMPS-D06. October 2003.

[Del7] Approaches for introducing passive system unreliability in accident sequence. **Deliverable 7** of RMPS project. EVOL-RMPS-D07. May 2003.

[Del8] Industrial Study Case, part 3. Integration of passive system reliability in PSA. **Deliverable 8** of RMPS project. EVOL-RMPS-D08. October 2003.

[Del9] Proposition of a specific methodology. **Deliverable 9** of RMPS project. EVOL-RMPS-D09. March 2004.

[Del10-11] Approaches for applying the methodology to VVER reactor and assessment of the improvement of analyses of VVER reactor. **Deliverables 10 and 11** of RMPS project. EVOL-RMPS-D10-D11. March 2004.

[Del12] Extended final report. **Deliverable 12** of RMPS project. EVOL-RMPS-D12. March 2004.

TABLES

Table 1: Comparison between the ranking of the parameters of the IC system: Standard Regression Coefficients from Sensitivity Analysis (columns 2 and 3) and AHP (column 4). The meaning of the symbols are the same as in table 2.

Rank	**Sensitivity Analysis**		**AHP**
	Flow Ratio	*Power Ratio*	
1	P1 (RPV)	P1 (RPV)	P1 (RPV)
2	L1 (RPV)	X1 (RPV)	X2 (IC)
3	X1 (RPV)	L1 (RPV)	L3 (pool)
4	POV (DR)	L2 (IC)	L2 (IC)
5	C2 (FD)	θ (FD)	T3 (pool)
6	T3 (pool)	POV (DR)	X1 (RPV)
7	UL (FD)	X2 (IC)	L1 (RPV)
8	X2 (IC)	L3 (pool)	θ (FD)
9	L2 (IC)	UL (FD)	POV (DR)
10	L3 (pool)	C2 (FD)	UL (FD)
11	θ (FD)	T3 (pool)	C2 : not available

Table 2: Uncertain parameters of the Isolation Condenser Passive system. Probabilities values for each critical parameter status are in bold-italics.

PARAMETER		DISCRETE VALUES						
P1	**RPV pressure (MPa)**	0.2	1	3	7	9		
		0.05	***0.1***	***0.15***	***0.5***	***0.2***		
L1	**RPV collapsed level (m)**	5	7	8.7	10	12		
		0.05	***0.1***	***0.5***	***0.2***	***0.15***		
L3	**POOL level (m)**	2	4.3	5				
		0.1	***0.8***	***0.1***				
Tp(0)	**POOL initial temperature (K)**	280	303	368				
		0.1	***0.8***	***0.1***				
X1	**RPV non-condensable fraction**	0.	0.01	0.1	0.2	0.5	0.8	1.
		0.719	***0.12***	***0.07***	***0.05***	***0.03***	***0.01***	***0.001***
X2	**Non-condensable fraction at the inlet of IC piping**	0.	0.01	0.1	0.2	0.5	0.8	1.
		0.71	***0.12***	***0.07***	***0.05***	***0.03***	***0.01***	***0.01***
θ	**Inclination of the IC piping on the suction side**	0.	1.	5.	10.			
		0.5	***0.4***	***0.08***	***0.02***			
C2	**Heat Losses piping - IC suction (kW)**	0.	5.	20.	100.			
		0.10	***0.7999***	***0.10***	***0.0001***			
L2(0)	**Initial condition liquid level - IC tubes, inner side (%)**	0.	50.	100.				
		0.1	***0.1***	***0.8***				
UL	**Undetected leakage (m^2)**	0.	1.e-5	5.e-5	10.e-5			
		0.8899	***0.1***	***0.01***	***0.0001***			
POV	**Partially opened valve in the IC discharge line – (%)**	1.	10.	50.	100.			
		0.001	***0.01***	***0.1***	***0.889***			

Table 3 : Probabilistic model of the 14 characteristic parameters for the RP2 system

Variable	**Distribution**	**Par 1**	**Par 2**	**X_{min}**	**X_{max}**
X_1, X_2	Truncated log-normal	0.12	0.43	0	1
L_1, L_2	Truncated normal	4.5	0.5	4	5
T_1, T_2	Truncated normal	30	20	10	50
C_1, C_2	Truncated log-normal	12	0.4	0	30
PUI	Truncated normal	100	2	98	102
PP	Truncated normal	155	2	153	157
ANS	Truncated log-normal	6	0.4	0	20
NGV_1, NGV_2, NGV_3	Truncated normal	12.78	0.70	12.08	13.91

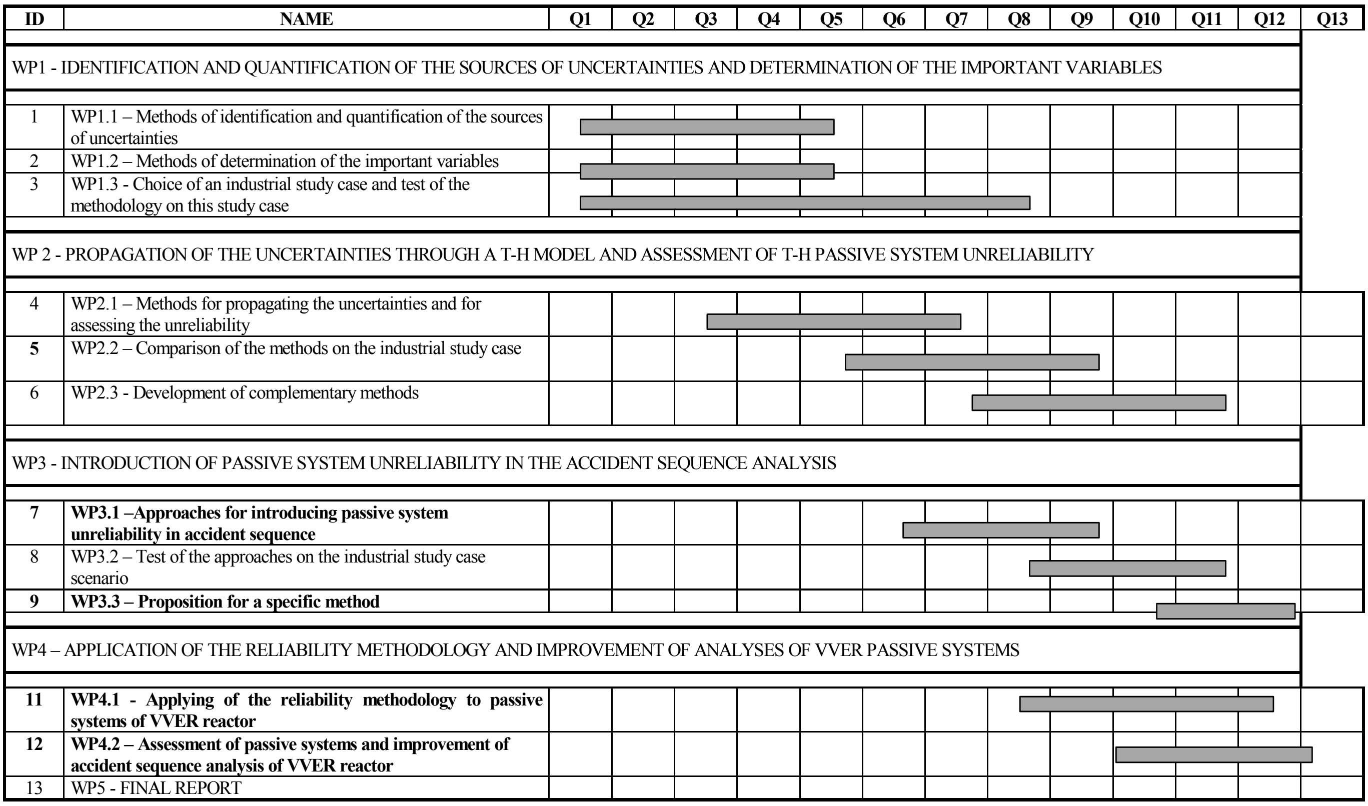
Table 4. Characteristic parameters considered for the analyses of the HA system

Parameter		Unit	Nominal value	Range
L	HA initial level	m	6.5	2.0 –6.5
P	HA pressure	MPa	6.0	3.0 – 11.0
T	HA initial temperature	^oC	20.	20. – 100.0
MCDC	Nominal CDC multiplier	-	1.0	0.6 – 1.6

Table 5. Discrete values of characteristic parameters of the HA system

Parameter	Value						
HA initial level, m	2.0		4.0		5.0	5.7	6.5
HA pressure, MPa	3.0	5.0	6.0	7.0	9.0	10.0	11.0
HA temperature, ^oC	20.0		40.0	60.0	75.0	90.0	100.0
CDC	0.6		0.8	1.0	1.2	1.4	1.6

FIGURES



ID	NAME	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13
WP1 - IDENTIFICATION AND QUANTIFICATION OF THE SOURCES OF UNCERTAINTIES AND DETERMINATION OF THE IMPORTANT VARIABLES														
1	WP1.1 – Methods of identification and quantification of the sources of uncertainties	▬	▬	▬	▬	▬								
2	WP1.2 – Methods of determination of the important variables	▬	▬	▬	▬	▬								
3	WP1.3 - Choice of an industrial study case and test of the methodology on this study case	▬	▬	▬	▬	▬	▬	▬	▬					
WP 2 - PROPAGATION OF THE UNCERTAINTIES THROUGH A T-H MODEL AND ASSESSMENT OF T-H PASSIVE SYSTEM UNRELIABILITY														
4	WP2.1 – Methods for propagating the uncertainties and for assessing the unreliability			▬	▬	▬	▬	▬						
5	WP2.2 – Comparison of the methods on the industrial study case					▬	▬	▬	▬	▬				
6	WP2.3 - Development of complementary methods							▬	▬	▬	▬	▬		
WP3 - INTRODUCTION OF PASSIVE SYSTEM UNRELIABILITY IN THE ACCIDENT SEQUENCE ANALYSIS														
7	**WP3.1 –Approaches for introducing passive system unreliability in accident sequence**						▬	▬	▬	▬				
8	WP3.2 – Test of the approaches on the industrial study case scenario								▬	▬	▬	▬		
9	**WP3.3 – Proposition for a specific method**										▬	▬	▬	
WP4 – APPLICATION OF THE RELIABILITY METHODOLOGY AND IMPROVEMENT OF ANALYSES OF VVER PASSIVE SYSTEMS														
11	**WP4.1 - Applying of the reliability methodology to passive systems of VVER reactor**								▬	▬	▬	▬	▬	
12	**WP4.2 – Assessment of passive systems and improvement of accident sequence analysis of VVER reactor**										▬	▬	▬	▬
13	WP5 - FINAL REPORT													

Figure 1: RMPS Gantt Chart (The unit of time is the Quarter).

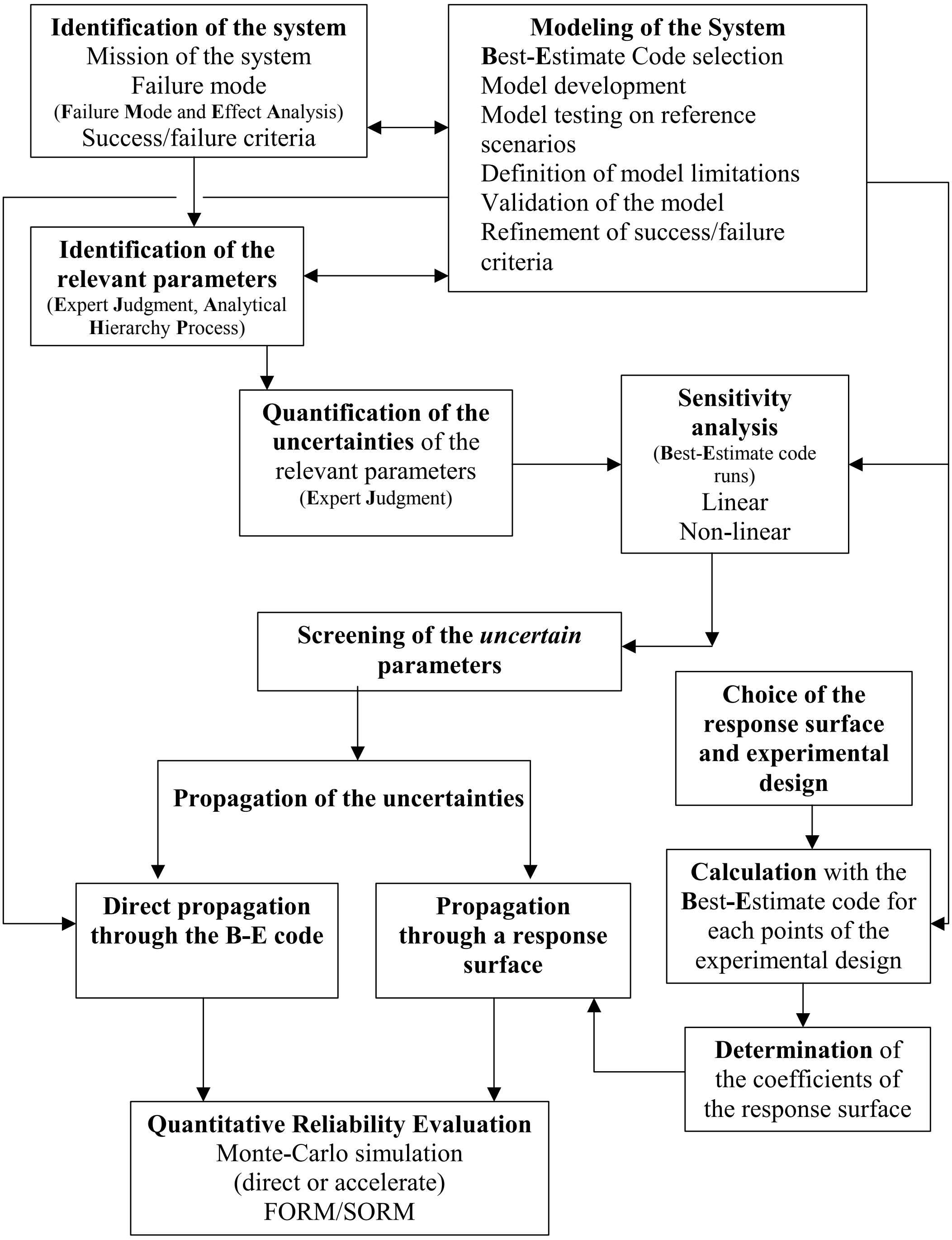


Figure 2: RMPS methodology roadmap.

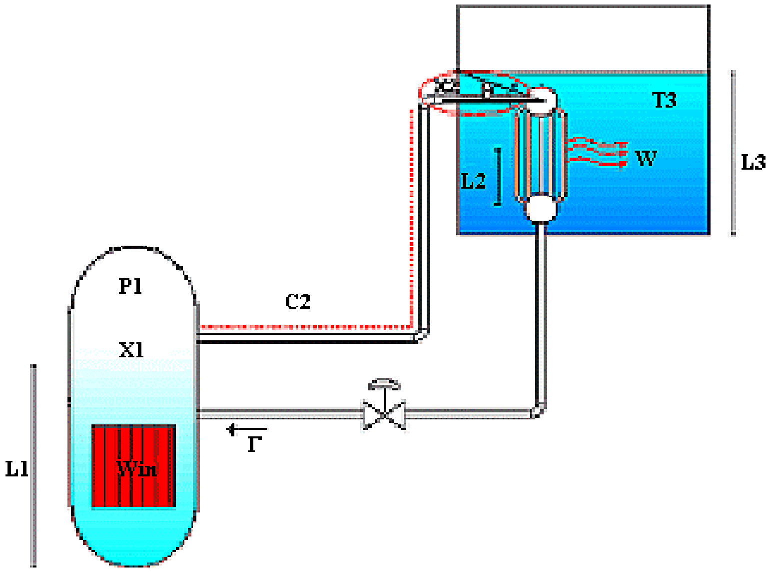


Figure 3: Standard Isolation Condenser as studied within the BWR

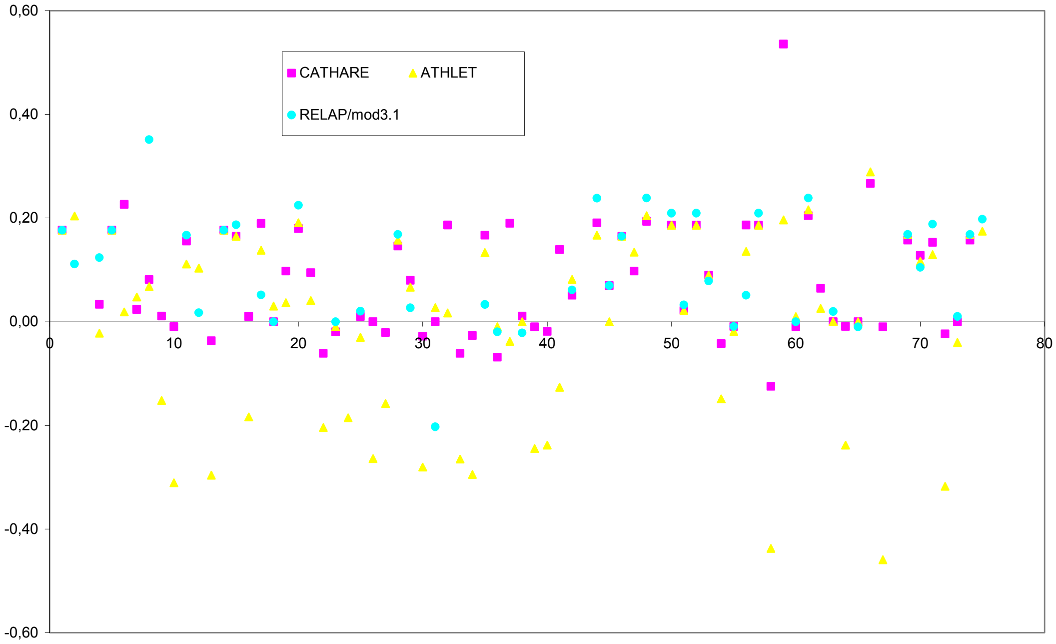


Figure 4: Relative difference between CATHARE, ATHLET or RELAP5/mod3.1, and RELAP5/mod3.2, obtained on the IC System.

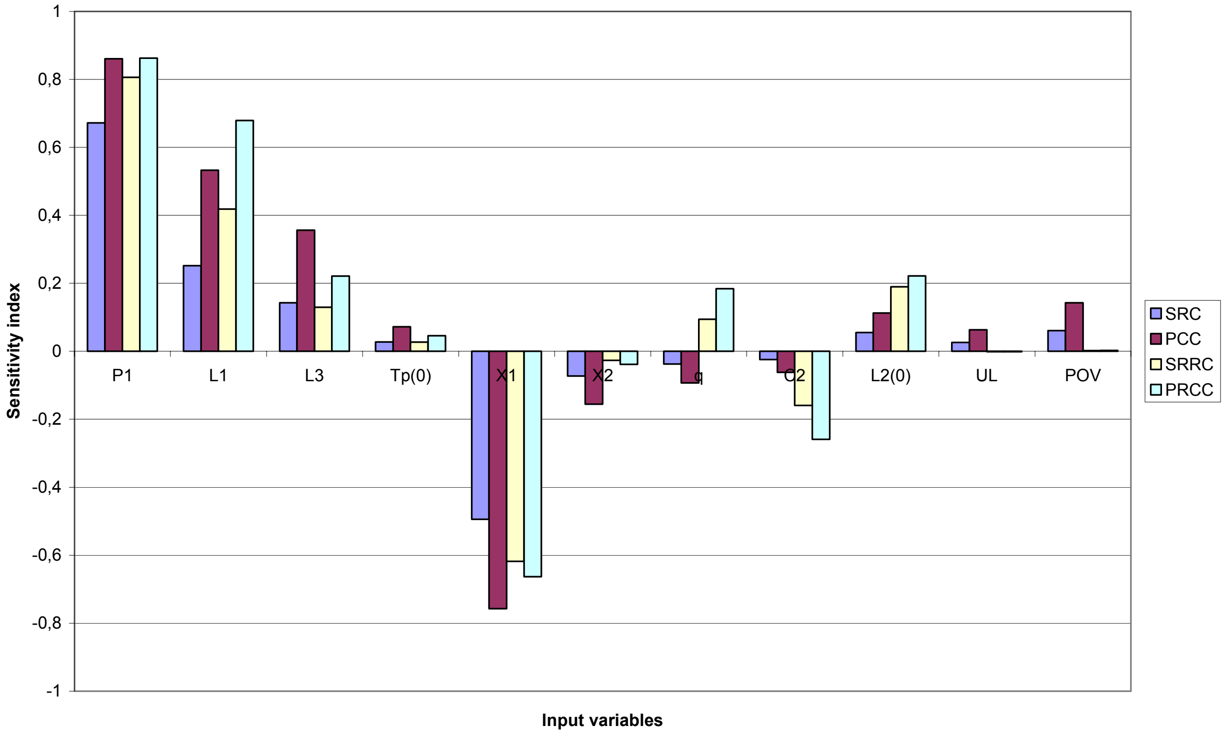


Figure 5: Sensitivity coefficients on the performance criterion of the IC System (CATHARE calculations)

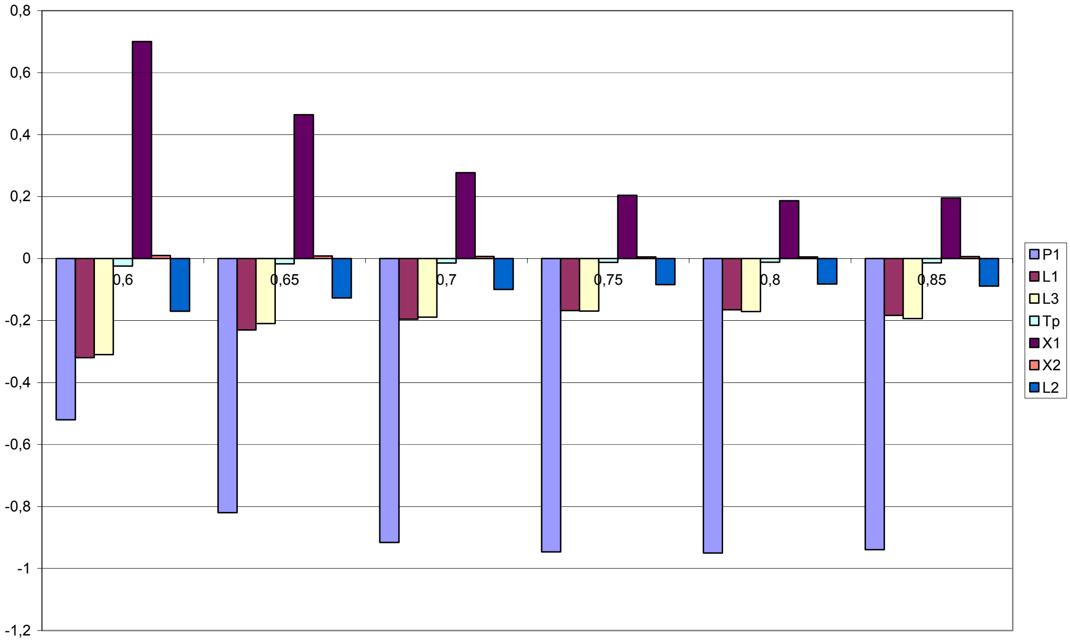


Figure 6: Evolution of the factors of sensitivity of the input variables with respect to the criterion limit α. (IC System)

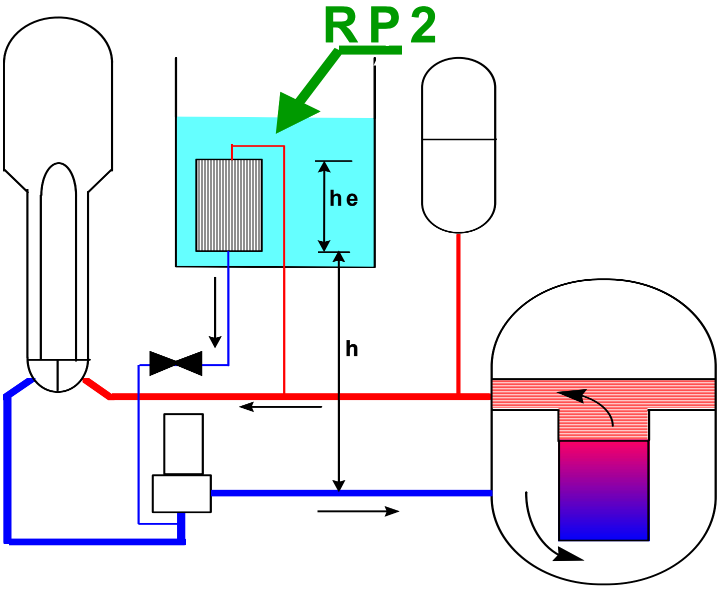


Figure 7: BOPHR/RP2 system

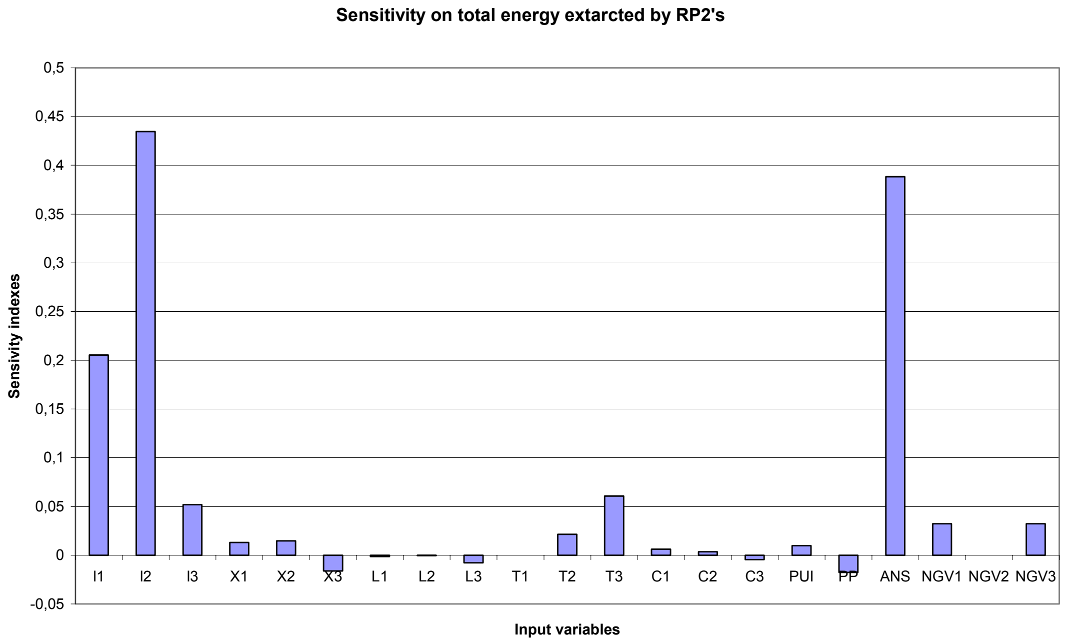


Figure 8: Sensitivity analysis (SOBOL indices) of the performance ratio of the RP2 system.

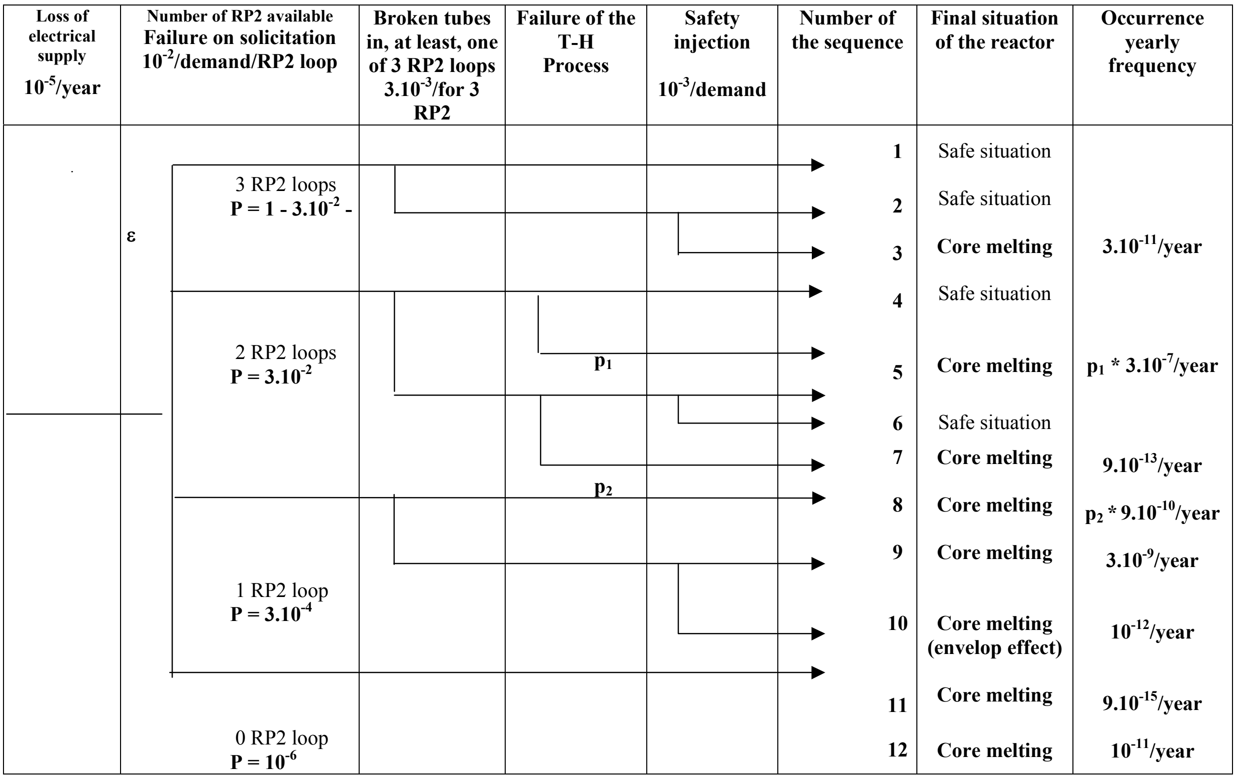


Figure 9 : Simplified Even Tree of Loss of Electrical Supply including Passive Systems

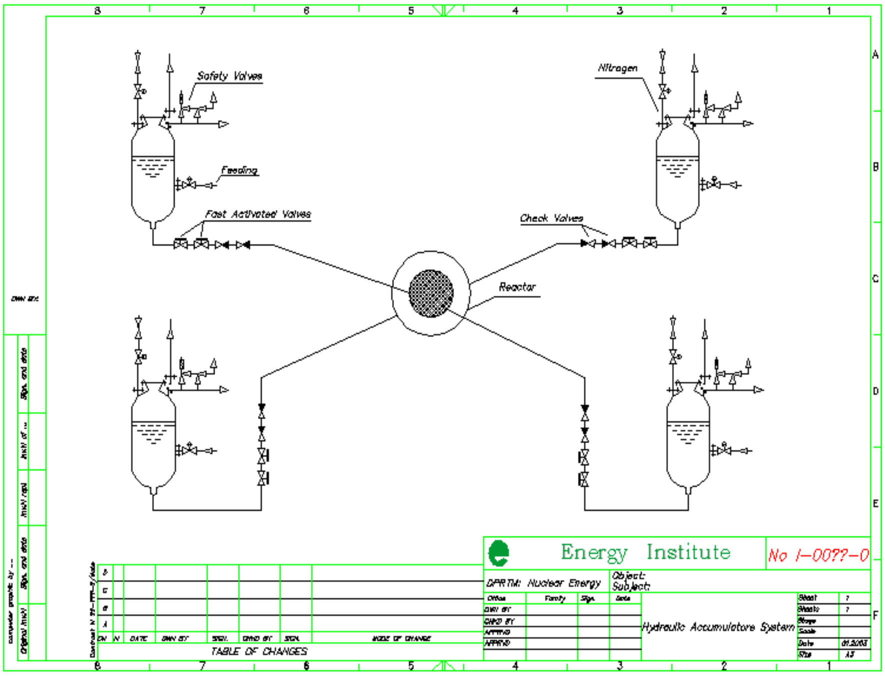


Figure 10: Hydro-Accumulator Passive System