PASSIVE SYSTEMS AND NUCLEAR THERMAL-HYDRAULICS

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ABSTRACT

Passive systems are in use within nuclear technology, noticeably those systems which are capable of transferring thermal power from a heat source to a sink with the use of energy coming from gravity: Natural Circulation inside the vessel for Boiling Water Reactors (BWR) and between vessel and steam generators for Pressurized Water Reactor (PWR) constitutes noticeable example. A step-wise, somewhat fashion-type, renewed interest followed after the three major nuclear accidents in 1979, 1986 and 2011. The words thermal-hydraulic passive systems, design and safety, open to a myriad of research and application activities, which without surprise may appear contradictory and, at least, not converging into a common understanding. In the present paper an attempt is made to use the word reliability in order to select a space in the design and safety assessment and to derive agreeable outcomes for the technology of passive systems. The key conclusions are: (a) passive systems are not the panacea for protecting the core of nuclear reactors in each foreseeable accident condition; (b) specific licensing rules are strictly needed and not yet formulated; (c) reliability of operation, once a target mission is assigned, may reveal not unit; (d) systems implying the use of active components like pumps shall not be avoided in future designed/built nuclear reactors.

KEYWORDS
Passive Systems Thermal-Hydraulics; Reliability of Passive Systems; Natural Circulation; Innovative Reactor Design

1. INTRODUCTION

Passive systems are embedded into the nuclear reactor technology design and safety since the beginning of the 'nuclear' era. In relation to design, the layout of primary systems of both Pressurized Water Reactor (PWR) and Boiling Water Reactors (BWR) is fixed based on natural circulation: the mutual positions of core and steam generators in the case of PWR and the elevation of the feedwater nozzle in the BWR vessel are designed to ensure (at least) removal of decay heat when active systems – noticeably, centrifugal pumps – are not available. In relation to safety, accumulators are one example of vital passive systems strictly needed to mitigate consequences of Large Break Loss of Coolant Accidents (LB-LOCA). Furthermore, any safety system, either active or passive, added to an already complex nuclear reactor designed to produce electrical power may introduce triggering causes for accidents and may interact with other existing system during the progression and eventually the mitigation of the accident.

Immediately after the Chernobyl accident in 1986, the passive systems received renowned attention by industry and scientists, noticeably and primarily in those Countries where that event had significant impact upon the exploitation of fission reaction for energy production. In other terms passive systems were taken as a remedy to unforeseeable situations, i.e. capable of mitigating or even avoiding the progression of accidents. The designs of Simplified Boiling Water Reactor (SBWR) and of the Advanced PWR (AP-600 and, more recently, AP-1000) were significant outcomes. The Fukushima accident in 2011 reinforced, in this case in all Countries, the interest towards passive systems, although those systems, ultimately, did not prove their effectiveness during the concerned event. Partly connected with above, the Three Mile Island accident in 1979 shifted the attention of nuclear safety analysists from LB-LOCA to

Small Break LOCA (SB-LOCA); i.e. accident scenarios dominated by natural circulation which constitutes a key phenomenon at the basis of the design of (selected) passive systems.

All major nuclear accidents have a connection with passive systems. Then, a synthesis view can be:

- Passive systems are part of nuclear technology.
- Passive systems are seen as inherently protective systems for the complex (whatever complexity, whatever unexpected situation) nuclear reactors.

The former item testifies, among other things, of a wide technical literature. The latter item may be taken as the visible tip of an iceberg of concerns, hopes, design activities and results of research activities connectable with passive systems: namely this is the concern for the present paper.

A universe of findings, situations and opinions actually characterizes passive systems; key-words connectable with related components or operation conditions are: accumulator, battery for powering Pilot operated Relief Valve (PORV), Isolation condenser (IC) Heat Exchanges (HEX), turbine and pump of Reactor Core Isolation Cooling (RCIC), condensation in Pressure Suppression Pool (PSP), natural convection in pools and containment open space, gas (noticeably hydrogen) stratification, natural circulation (NC) during Core Make-up (CMT) draining, Steam Generator (SG) cooling of the core, condensation on containment wall, electrical wire, channel blockage caused by debris, instability in a single boiling channel or in parallel channels, quench front progression during reflood, etc. One may also argue that the recently issued list of 116 thermal-hydraulic phenomena for code validation which are expected to cover Design Basis Accident (DBA) conditions in Water Cooled Nuclear Reactors (WCNR), [1], is entirely applicable to passive systems with the exception of a couple of phenomena dealing with centrifugal pumps and fans.

It is understandable that: (a) any generic statement about passive systems may become questionable or invalid in each of the applicable situations; (b) fields for passive systems research are in number which cannot be easily quantified. Therefore there should be no surprise that a recent effort completed within International Atomic Energy Agency (IAEA) framework, [2], concludes that there is ‘clear need to obtain more data’ and ‘more practical approach [for the evaluation of reliability of passive systems] would be very helpful’; still a new international project has been planned and just started by the Committee on the Safety of Nuclear Installations (CSNI) of Nuclear Energy Agency (NEA) part of Organization for Economic Cooperation and Development (OECD), [3].

At this point it is clear that one paper may not reasonably cover or even touch all the aspects connected with passive systems. Rather, the objective here is to discuss the connection between nuclear thermal-hydraulics and passive systems. This (i.e. the objective) can be defined as <how the thermal-hydraulics models and procedure are applicable and relevant to the evaluation of the reliability of passive systems>. The scope for the paper is restricted to a *virtual natural circulation loop* consisting of suitable heat source and heat sink in a gravity environment; the findings can be used for the reliability evaluation of more complex system. Noticeably, no discussion about the classification of passive systems [4] and no answer shall be expected from the paper in relation to the reliability of:

- Small Modular Reactors (SMR), operational and accident conditions;
- AP-1000, accident conditions;
- mechanical, electrical and electronic components;
- the natural circulation in established situations like ‘inside the BWR vessel’ (including related thermal-hydraulic and neutron physics stability considerations) and ‘between core and steam generators of PWR’; see e.g. [5] and [6];

2. RELIABILITY (OF A SYSTEM) AND UNCERTAINTY (OF A CALCULATION)

The concepts of reliability and uncertainty are well established in various fields of scientific literature: theory of probability and application of computational tools to solve complex problems in nuclear thermal-hydraulics constitute example frameworks, respectively. The focus hereafter is the application of those concepts to the evaluation of transient performance of passive systems:

- An applicable reliability concept may be easily derived considering the pushing of a switch aimed at interrupting the electric current flowing in a wire: if one pushes the switch from its original position (electrical current flowing) 1000 times and he finds that the current does not stop 3 times, he may conclude that the reliability of the system (i.e. the switch) is 99.7%.
- An applicable uncertainty concept needs at least identification of thermal-hydraulic phenomena, computer code development, validation and use in simulating the performance of a system, identification of uncertainty origins and availability of an uncertainty method. The description and/or the understanding of the concept cannot be summarized in a few lines: the reader should consider reference documents, see e.g. [7].

The application of the reliability concept needs a target mission for the system (i.e. the interruption of the electric current) and an action to compare the target mission with the actual performance of the system. Otherwise, the output of the application of an uncertainty method needs suitable qualification and demonstration of usefulness: e.g. if the predicted uncertainty in calculation output parameters is very large, it is of little use in practical applications and the knowledge of the concerned thermal-hydraulic phenomena may need improvement.

Now, let’s consider as reference system the virtual natural circulation loop. This consists of a pressure vessel surrounding the core (heat source) and of an external ambient pressure water pool surrounding enclosing the IC (heat sink). The following minimum list of steps to perform the activity of evaluating the reliability of the system is needed:

1) To fix a Target Mission (TM) for the system: in this case the target mission is the removal of thermal power keeping the integrity of the core.
2) To consider the envelope of situations, i.e. boundary and initial conditions, in relation to which the system is called into operation.
3) To identify ‘all’ possible situations, and assigning a Probability to each situation or Mission (PM).
4) To perform analyses (calculation) in relation to each situation.
5) To compare calculation results with the target mission.

Two critical issues may be identified at this point in addition to the issue of identifying ‘all’ possible situations:

A) The target mission for the *reliability* evaluation is not as simple as in the case of the switch used to stop the electrical current. Rather the target mission should be connected with thermal-hydraulic phenomena unavoidably implying a transient nature.
B) The calculation of the target mission implies the use of a computational code and the unavoidable occurrence of *uncertainty*.

The cornerstone achievement at this point can be synthesized as follows:

<*we need to calculate the reliability of a thermal-hydraulic phenomenon*
whose evaluation is affected by uncertainty>.

Here we face with an inherent ambiguity: on the one hand the actual (expected, not known) system performance (then, the *reliability*) is **not affected** by the capability of adopted computational tools, which shall be quantified by the uncertainty; on the other hand, any possible reliability evaluation **is affected** by uncertainty.

In order to solve the ambiguity, already within the first-pioneering proposal of a procedure to evaluate the reliability of a passive system, [8], see also [9], the proposal was made to disconnect uncertainty and reliability: namely, the reliability is the characteristic of a system and the uncertainty is the characteristic of a calculation.

Therefore, the reliability is calculated assuming that the code is ‘perfect’ (‘zero’ uncertainty) in predicting thermal-hydraulic phenomena expected in the concerned passive system. Then, the impact of uncertainty is evaluated upon the reliability value.

2.1 Insights into TH Code Application

The application of thermal-hydraulic system codes within nuclear reactor safety and design constitutes a broad topic widely discussed in technical literature, see e.g. [10], also needing to address the scaling issue, see e.g. [11]. The following notes supplement and/or justify the assumption of disconnecting the uncertainty evaluation from the reliability evaluation when applying a system thermal-hydraulic code to the analysis of a passive system.

The first note deals with parameter ranges. When looking at parameters ranges expected in the operation of the concerned passive system, i.e. pressure, temperature, steam and liquid velocity, heat transfer coefficient and connected temperature differences, geometry of components including hydraulic diameters, etc., the outcome is that the code is qualified within those parameter ranges including their combinations.

The second note deals with prediction errors. The analysis of experimental data involving passive systems including experiments performed at full scale (pressure, geometry and exchanged power) of IC, show ‘small’ errors (or in-accuracy), or small expected uncertainty bands. The largest contribution to the error is expected to be due to pressure drop coefficient (K_{LOSS}) at geometric discontinuities which may not be considered an inherent code limitation: rather K_{LOSS} values are supplied by code user and may need specific experimental data. The outcome here is that uncertainty in the prediction of passive system performance (excluding the part associated with K_{LOSS}) is negligible (see also next section).

The third note deals with scaling. As a difference from typical phenomena relevant to nuclear reactor safety, large scale or even ‘scale 1’ experiments are available for passive systems. This avoids or reduces the importance of scaling issue. The outcome strengthens the conclusion at the previous note: the uncertainty in the prediction of passive system performance (alone) is negligible.

The fourth note deals with the reliability and the uncertainty in predicting the behavior of the passive system installed within a complex NPP system. Interactions between an assigned passive system and the other regions of a nuclear reactor may reveal a source of instabilities, among the other things; this largely increases error bands of predictions (i.e. the uncertainty) and directly the reliability. The outcome is that even if the reliability of a passive system alone is suitable, a problem (low reliability) may occur when the system becomes a part of a more complex system.

3. RELIABILITY EVALUATION FOR THE CONCERNED PASSIVE SYSTEM

As an overall result from the previous sections we have that: (a) reliability of a passive system may be reduced to the reliability of thermal-hydraulic phenomena expected during the operation of the system, and (b) reliability can be distinguished and disconnected from uncertainty when analyses are performed.

The (not-agreed by international scientific community) distinction between uncertainty and reliability, as already mentioned is at the basis of the present paper; the diagrams in Figs. 1 and 2 are helpful for the discussion below.

3.1 Reliability calculation

The Target Mission (TM) and the Probability of Mission (PM) are envisaged quantities to calculate the reliability of a passive system. Reliability of NC in the reference passive system is of concern here.

The calculation of PM requires the identification of the passive system Boundary and Initial Conditions (BIC), also called event-BIC, or the system status conditions (the latter case not supported by performed analyses known to the author) and the consideration of the Origin of Un-Reliability (OUR). Examples of BIC quantities are the pressure, the core power and the distribution of fluid temperature in the system pipelines at the time when the passive system operation is triggered. OUR quantities are discussed in section 3.5. Suitable techniques are needed to evaluate the probability of an initial status for the passive system operation by combining BIC and OUR, see e.g. [12].

The calculation of TM implies the knowledge of the system design conditions: in the concerned case the TM is expected to be a function of the thermal energy removed from the heat source (i.e. core decay heat) during an assigned time period. Several conditions (e.g. mass flow-rate or margin to Departure from Nucleate Boiling [DNBR] greater than assigned values for an assigned time period) may be added to form the TM. The calculation of TM typically needs a thermal-hydraulic computer code as already mentioned. TM and PM can be either connected to the (passive) system status, e.g. pressure, level and power of operation, or to an initial set of conditions (e.g. pressure and level) when the passive system is called in operation.

TM and PM may be related in a diagram as in Fig. 1: each open bullet constitutes the outcome of a calculation which: (a) is performed starting from one PM value and, (b) results in one TM value. A line connecting the open bullets, hereafter called the reliability line, separates reliability and un-reliability regions. Looking at the value PM* one may note that different TM values may be associated to a single PM: the lowest TM value is used to build-up the reliability line. The system reliability may be assumed as connected with the integral of the dotted region above the reliability line: possibly more weight can be given to the TM values close to the region PM = 1.

In the horizontal axis in Fig. 1 (see also Fig. 2) a continuum probability of event or statuses is assumed with their probability integral equal to 1: for instance, making reference to a BWR it is expected that the IC enters and/or remains in operation when, (1) the level of downcomer is within a range A-to-B (where, reasonably, A and B can be 3 and 10 m, respectively), (2) the core power is in a range 0.5% to 4% of nominal power (e.g. not 30% core nominal power) and (3) the system pressure is in the range 0.2 to 9 MPa.

The outcome from Fig. 1 is a probability (horizontal axis, e.g. of an initial set of conditions for the start of a passive system or a set of conditions identifying a system status) versus the achievement of a designed target (vertical axis, associated to either a set of an event-BIC or of system status). If a unique value for reliability is calculated for a passive system, either having a relative or an absolute meaning, proper weight can be assigned to each point of the curve (e.g. low PM values may have a weight lower than high PM values): in mathematical terms an integral value is envisaged.

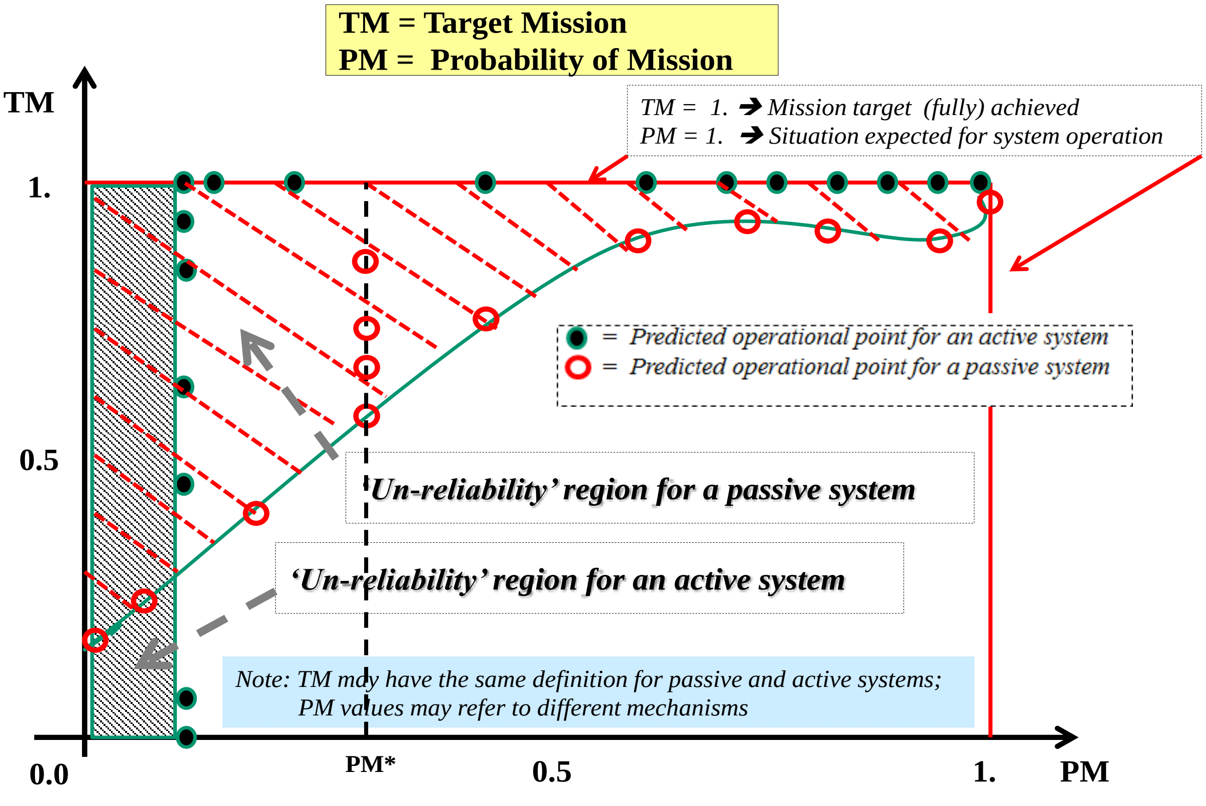

Figure 1. Reliability of the reference passive system and comparison with reliability of an active system having the same design mission.

3.2 Comparison between Equivalent Passive and Active Systems

TM and PM values, as well as the reliability line, have a recognizable relative meaning, although an effort can be made to associate those values and an absolute meaning. Considering the relative meaning, it seems essential to compare the calculated reliability of a passive system with the reliability of an active system having the same mission as the concerned passive system. This is done in Fig. 1: the dense-dotted area on the left (low probability region) is derived.

Within nuclear reactor safety, a passive system, other than a lower cost, should show to have a better reliability figure-of-merit than an equivalent active system (a gauss-like probability distribution might be considered for active systems, rather than a line).

A variety of situations and questions may occur in practice, in addition to one passive system substituting an active system (and related demonstration that the passive system is better), e.g.:

a) one passive system is designed as back-up of an existing active system;
b) is the assigned passive system [A] better than the assigned passive system [B]?
c) a reduced quality grade active system is used as back-up of a passive system;

d) two passive systems used instead of one active system (or vice-versa);
e) etc.

In each case, a specific probabilistic safety type of analysis may be needed before entering into a reliability analysis. Further insights are related hereafter to the simplest situations.

3.3 Optimization of the Design of a Passive System

The reliability method, generating TM, PM and the reliability line, may be applied to address questions like the following ones where the system [A] is the already mentioned virtual natural circulation system to the reliability line in Fig.1:

- Is a new system (system [B]) designed with a higher (or lower) elevation of the heat sink (or the pool which includes the heat exchanger) related to the core better in terms of reliability than system [A]?
- Is a new system (system [B]) characterized by two heat exchangers instead of one better than system [A]?
- Is a new system (system [B]) characterized by larger pipe diameter connecting the RPV and the HEX better than system [A]?
- Etc., including combinations of the above.

The possible answer to (each) one of the questions is another reliability line (not shown in Figs. 1 and 2). System [B] may result to be better or worse than system [A]: proper reliability analysis is needed to finalize the comparison between system [A] and system [B].

3.4 Role of Uncertainty

The reliability and the uncertainty in predicting the performance of a passive system stand-alone may be different from the case when the performance of an overall nuclear reactor system (the NPP) equipped with a passive system is concerned. Key situations are depicted in Fig. 2 where expected impact of uncertainty upon reliability prediction is visualized:

- ⇨ The uncertainty in predicting reliability relevant scenarios for the system sketched in Fig. 1, passive system alone, moves the reliability line from curve “1” to curve “2” (thin black arrows in Fig. 2): vertical arrows represent (small expected) errors associated with the evaluation of TM by a system thermal-hydraulics code and horizontal arrows are associated with errors in estimating PM.
- ⇨ The outcome of reliability analysis of the passive system embedded into the overall reactor system (or the NPP, i.e. with all systems reacting; in other terms the same analysis performed for the passive system alone is now repeated with all other systems modeled), may reveal different from curve “1”; reliability line “3” may result.
- ⇨ The uncertainty in predicting reliability relevant scenarios for an overall NPP, which includes the virtual natural circulation system, moves the reliability line from “1” to “4” in Fig. 2: vertical arrows represent (large expected) errors associated with the evaluation of TM by a system thermal-hydraulics code; in this case the same horizontal arrows are associated with errors in estimating PM (not shown in the diagram).

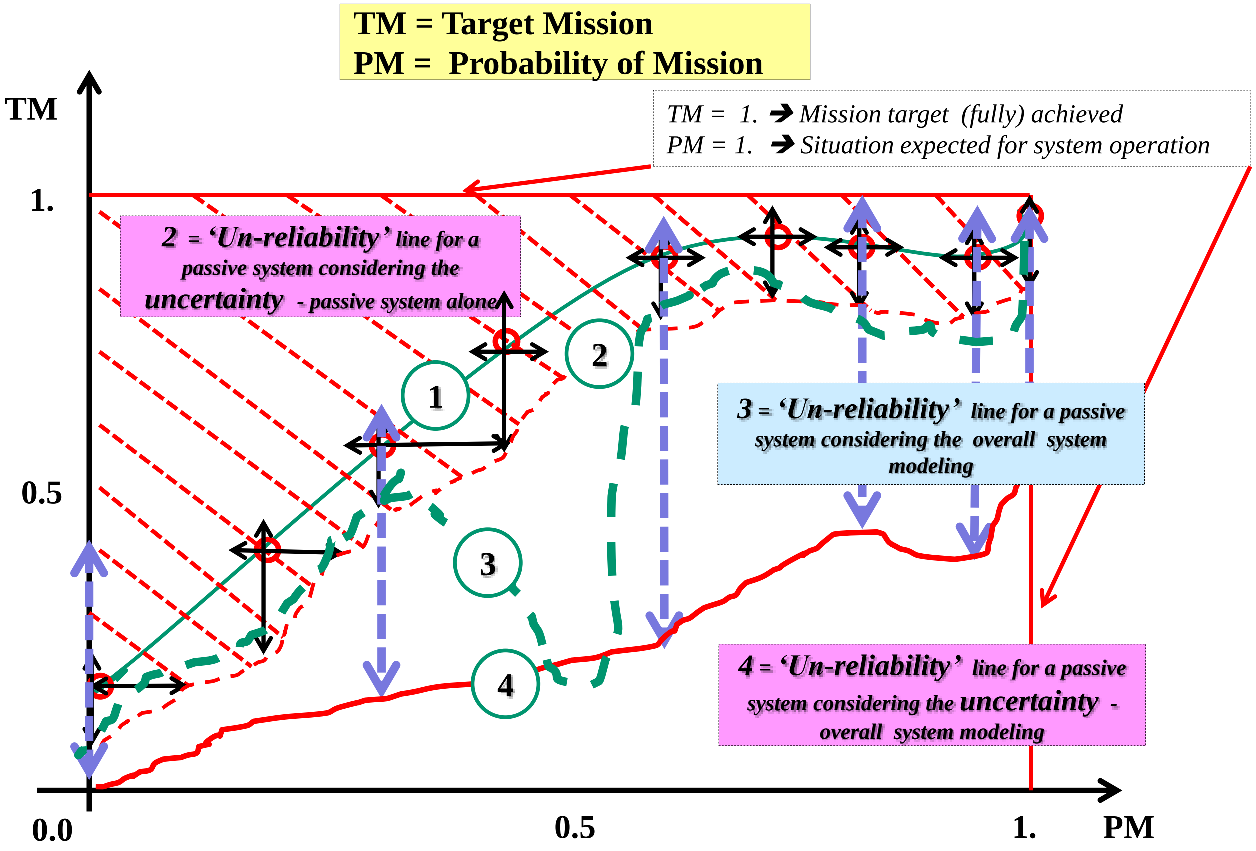

Figure 2. Reliability of the reference passive system and impacts of uncertainty of code prediction considering the passive system alone and the passive system interacting with other systems in the plant [line "1" is the reliability line expected for the passive system alone, see Fig. 1].

Making reference to Fig. 2, it shall be noted that reliability line "1" is the outcome of a reliability calculation where the adopted computational tool is assumed to be without errors (or 'perfect'). The line "1" is expected in case a large number of scale-1 experiments are performed or when code results are properly validated.

Furthermore, the lines "2" to "4" need the application of computational tools. Namely, the line "2" is expected to be close to the line "1" because of suitable validation of current computational tools. The lines "3" and "4" imply modeling of the overall system (the NPP): line "3" is the outcome of the analysis when reliability origins (passive system alone embedded into the overall system) are considered and line "4" is the outcome of the analysis when uncertainty origins (related to the overall system) are considered.

3.5 The Origins of Uncertainty and Un-reliability

The origins of uncertainty in thermal-hydraulic code predictions were proposed early in 1998, [13], and later on spread in various papers and documents, see e.g. [14]. Namely, the origins of uncertainty are connected with imperfect modeling (also called epistemic) and imperfect knowledge of boundary conditions (also called aleatory); the latter group providing lower contribution to the overall uncertainty. Methods to evaluate the uncertainty are discussed in available literature, see also [7].

The reasons or the origins of un-reliability for passive system can be found in papers discussing the reliability of passive systems, see e.g. [2], [8], [9], [12], [15] and [16]. The origin of un-reliability shall be connected with the design and the operation characteristics of the (passive) systems.

As a key difference from the origins of uncertainty, no epistemic (nor aleatory) unknowns is distinguished; rather, parameter ranges which characterize the design of the (passive) systems are involved.

Table I has been built in order to clarify the differences between physical quantities at the origin of uncertainty and reliability. Starting from right to left in the table (3rd to 5th column), three categories of selected parameters are distinguished affecting: (3rd column) 'uncertainty of thermal-hydraulic phenomena expected in the operation of the passive system stand-alone'; (4th column) 'uncertainty of thermal-hydraulic phenomena expected in the operation of the passive system embedded into the nuclear reactor'; (5th column) 'reliability of passive system design'. The table makes reference to the virtual natural circulation system and to the expected results from reliability and uncertainty studies, e.g. Figs. 1 and 2.

Table I – List of quantities affecting reliability and uncertainty analysis of the virtual natural circulation passive system.

No	QUANTITY IDENTIFICATION	UNCERTAINTY		RELIABILITY	NOTES
		Passive System (°)	NPP with Passive System(°)	Passive System Design(°)	
1	Pressure		X		Aleatory, e.g. +/- 0.8%
2	Pressure			X	Range*, e.g. 0.2 – 9 MPa
3	Core power		X		Aleatory, e.g. +/- 10%
4	Core power			X	Range*, e.g. [0.1-4]%
5	HEX heat transfer coefficient	X			Epistemic
6	Heat losses IC piping			X	Range*
7	Countercurrent flow in core		X		Epistemic
8	Two phase critical flow		X		Epistemic
9	K_{LOSS} various locations of IC	X			Epistemic
10	K_{LOSS} various locations of NPP		X		Epistemic
11	DNB or margin to DNB			X	Appearing in TM
12	Partial opening of IC valve			X	Range*
13	Horizontal pipe inclination			X	Range*; irrelevant for active systems
14	Non-condensable gas in IC pipe			X	
15	Elevation of IC pool			X	Alternative passive system design optimization
16	No of HEX in the pool				
17	Diameter of IC piping				

(°)Relevant to Fig. 1 and 2; *to be specified by IC designer; expected for operation of the passive system; range split in several regions which correspond to a probability

3.6 Attributes of a reliability study

A comprehensive reliability study supported by uncertainty analysis is expected to provide methodological approaches:

- to identify a full list of parameters distinguishing into three categories as given in Table I;

- ⇨ to characterize the range of variations of parameters (see e.g. [8]);
- ⇨ to identify and to characterize the Target of Mission and the Probability of Mission (TM and PM as introduced in Fig. 1), see e.g. [12];
- ⇨ to derive the reliability lines (e.g. as defined in Figs. 1 and 2) and to identify (as far as possible) objective values for the system reliability which can compare with the reliability of components of equivalent active systems;
- ⇨ to allow the comparison between a passive system and an active system having the same Target of Mission, see also Fig. 2;
- ⇨ to allow the optimization of the design of a passive system, see also Fig. 1;
- ⇨ to perform supporting uncertainty studies (as introduced in Fig. 2), see e.g. [7].

Results from the reliability study shall include diagrams as those in Figs. 1 and 2.

5. CONCLUSIVE REMARKS

The reliability of operation of a natural circulation passive system suitable for nuclear power plant technology is at the center of attention in the paper. Three areas for conclusive remarks are identified below.

A) The Natural Circulation. When water is used as acting fluid assuming typical (design detail) elevation differences between source and sink or, driving head, expressed in *meters of liquid water at ambient pressure and temperature* is of the order in the range $\underline{10^{-1} \div 10^{0}}$, when single-phase and two-phase conditions are concerned in the system design, respectively. Those values should be compared with values in the range $\underline{10^{1} \div 10^{2}}$ when (typically centrifugal) pumps are installed in similar loops: capabilities of a passive system are compared with the capabilities of an equivalent active system having the same design target.

B) The reliability (of a system) and the uncertainty (of a calculation). The concepts of reliability and uncertainty and the related methods are basically different. It is proposed to perform uncertainty analysis at two levels following a reliability study. The former is concerned with the passive system alone and may not bring to substantial changes in the reliability figure. The latter is concerned with the entire system e.g. the NPP where the passive system is installed and may dramatically decrease the reliability of the passive system.

C) The attributes of a reliability study. Suitable methodologies are needed to perform a reliability analysis. Design conditions for a passive system should be identified first. Target of Mission (TM) and Probability of Mission (PM) should be defined and shall constitute the objective of calculations. Parameters at the origin of reliability shall be characterized. The envelope of calculation results may constitute a reliability line and a measure of the objective reliability of the concerned passive system. Reliability of a passive system alone may be different from reliability of the same system (with the same mission) as part of a complex system (e.g. the nuclear reactor). Uncertainty analysis is needed to support reliability evaluation.

The key conclusions are:

- ➢ A passive system or a passive system as a substitute of an active system is not a synonymous for increased safety.
- ➢ Wide design choices and related parameters exist for a passive system (as well for an active system, not of concern here); this also includes the issues of redundancy for passive

components: the estimation of the design quality needs proper transient thermal-hydraulic analyses.

- Reliability analysis shall be distinguished from uncertainty analysis, although a comprehensive reliability analysis including uncertainty is needed. Procedures to determine reliability are available to scientific community; the reliability of operation of a passive system, once a target mission is assigned, may reveal not unitary.
- Passive systems may reveal worthwhile for nuclear technology; however reliability analysis is needed accomplishing licensing targets that may not be yet available.
- Within an overall system safety evaluation the demonstration should be achieved that a passive system is better than an equivalent active system performing the same function. Probabilistic and deterministic techniques are available and should be used.

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