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EVALUATION OF THE RELIABILITY OF A PASSIVE SYSTEM

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ABSTRACT

A passive system should be theoretically more reliable than an active one. In fact its operation is independent by any external input or energy and is relied only upon natural physical laws (e.g., gravity, natural circulation, etc.) and/or "intelligent' use of the energy inherently available in the system (e.g., chemical reaction, decay heat, etc.). Nevertheless the passive system may fail its mission as consequences of component failures, deviation of physical phenomena, boundary and/or initial conditions from the expectation.

This document describes at first the methodology developed by ENEA, in collaboration of University of Pisa and Polytechnic of Milano, allowing the evaluation of the reliability for a passive system, which operation is based on moving working fluids (type B and C, cf. IAEA). It reports the results of an exercise performed on a system, which operation is based on Natural Circulation.

1 INTRODUCTION

Passive systems deserve a special attention within the nuclear technology owing to their potential to reduce the cost for the production of electricity and to enhance the safety level of power plants [1].

The accomplishment of the objectives of increasing the safety level and reducing the cost through the reliance on natural circulation mechanisms requires a deeper knowledge of those mechanisms for characterizing and assessing the passive system performance and reliability. These are usually characterized by smaller driving forces with respect to the similar mechanisms involved when an external source of energy for the fluid motion is involved. For instance, pressure drops caused by bends and siphons in a given loop or heat losses to environment may not put any concern to the designer when a pump is installed and drives the flow through the piping. On the contrary, a significant influence upon the overall system performance may be expected when Natural Circulation (NC) is present and undergoes the same pressure drops and thermal power release to the environment. Therefore, the level of knowledge for the thermal-hydraulic phenomena expected at the geometric discontinuities or governing heat transfer should be deeper when NC is involved.

Passive systems should be theoretically more reliable than active ones. In fact they usually do not require any external input or energy to operate and they rely only on natural physical laws (e.g., gravity, natural circulation, internally stored energy, etc.) and/or inherent energy available in the system (e.g., chemical reaction, decay heat, etc.).

Nevertheless passive systems may fail their mission as consequences of component failure, or for deviation of physical phenomena, boundary and/or initial conditions from the expectation.

The state of art on methodologies and applications about the assessment of passive system reliability shows the research activities are in progress and they are not consolidate. Besides they concern mostly single aspects rather than an overall view of the problems [2, 3, 4, 5 and 6].

This research, carried out in ENEA in collaboration of University of Pisa and Polytechnic of Milano since 1999, is finalised to the development and validation of a methodology allowing the evaluation of the passive system reliability, which operation is based on moving working fluids (type B and C, cf. IAEA) [7].

This document describes this methodology and reports the results of an exercise performed on a system, which operation is based on Natural Circulation. The selected system is a loop including a heat source and a heat sink where the condensation occurs. Its configuration is typical of the Isolation Condenser, part of the SBWR design. Selected ranges of operating conditions (pressure, fluid velocities, and heat transfer coefficients) include values expected for the same system and reported in bibliography.

2 METHODOLOGY OVERVIEW

For evaluating the failure probability of passive systems, the developed methodology resorts to the classical methods used for Probabilistic Risk Analysis and considers, in addition to real components (valves, pumps, instrumentation, etc), virtual components, that represent the natural mechanism upon which the system operation is based (natural circulation, gravity, internal stored energy, etc.). Therefore the reliability of passive systems may be achieved evaluating the failure probability of all the components (real and virtual).

The contribution of real components can be easily assessed by resorting to the reliability databases available, based on fission reactor experience, whereas for evaluating the virtual component contribution it is necessary to develop a procedure which allows to reach this purpose because of the lack of failure data.

The procedure proposed by ENEA, University of Pisa and Polytechnic of Milano foresees several steps, which are listed below:

1) Characterization of design/operational status for the system and assignment of probability distribution to the *design parameters*. These parameters are those closely related to the mission of the system. The full characterization of a thermal-hydraulic system may need a very large, hence unmanageable, number of such quantities. Therefore, a bounded number of parameters should be selected.

2) Selection of *critical parameters* for the system operation and their probability distribution. The parameters identified as critical are those physical quantities that may affect the mission of the passive system. As in the previous point, a huge number of parameters could be required to fully characterize the system operation. Therefore an effort must be done to select a bounded number of parameters.
3) Definition of failure criteria for the system performance. The knowledge of the system mission allows the evaluation of the failure criteria. These criteria can be established both as single-value targets (e.g., the system must deliver a specific quantity of liquid within a fixed time) and 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).
4) System analysis, that is modelling of the system by a qualified thermal-hydraulic system code and performing best estimate calculations for each set of boundary and initial conditions selected in function of the assigned probability of design and critical parameters.
5) Evaluation of *system performance indicators* and failure rate. Based upon failure criteria and results of code calculations, system performance indicators and failure rate could be derived. Curves of merit for the system performance can be assumed to be characteristic of the selected thermal-hydraulic system and can be used to judge the system acceptability and to compare the selected system with other different passive systems.

The authors want to point out that the development activity is still in progress and improvements of this procedure are certainly necessary. Among them, for instance the identification the most important parameters with respect to system unreliability, or the identification of the top failure criteria, e.g. via Analytic Hierarchy approach.

3 SELECTED PASSIVE SYSTEM AND RELEVANT PARAMETERS

A passive system having a configuration relevant to the technology of currently advanced Light Water Nuclear Reactors has been selected for the application of the procedure. The system consists of a pressure vessel and a heat exchanger immersed in a pool. The pool and the heat exchanger are at a higher elevation than the power source. The selected configuration and the operating conditions are typical of the Isolation Condenser, that is part of the SBWR design, whereas the operation of this system has been supposed different. A concept scheme of the system is given in Figure 1.

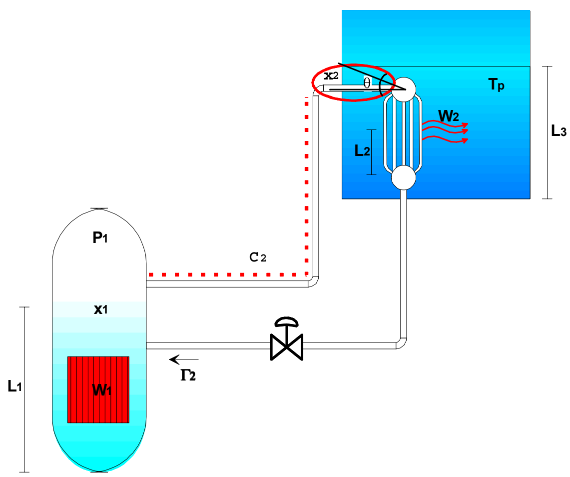

Figure 1 : Scheme of the selected passive system

The identified design parameters of the passive system, together with the proposed values are reported in Table 1. The nominal values, the ranges of variation and the selected initial values for the analysis are distinguished. The probability values for each initial status are reported in bold-italics.

Table 1 – Design parameters of the passive system.

Parameter		Unit	Nominal Value	Range	Discrete Initial Values				
P_1	RPV pressure	MPa	7	0.2-9	0.2	1	3	7	9
					0.05	***0.1***	***0.15***	***0.5***	***0.2***
L_1	RPV collapsed level	m	8.7	5-12	5	7	8.7	10	12
					0.05	***0.1***	***0.5***	***0.2***	***0.15***
L_3	POOL level	m	4.3	2-5	2		4.3		5
					0.1		***0.8***		***0.1***
$T_p(0)$	POOL initial temperature	K	303	280-368	280		303		368
					0.1		***0.8***		***0.1***
-	System geometry : layout	-	-	Not assigned	-				
					1.0				

The initial values, last column in Table 1, are based on an engineering judgement. The derivation of these values is necessary in order to associate a probability value of occurrence for each system configuration and thus for each system performance evaluation, that could lead to a system failure.

It is assumed that the system RPV+IC+piping+valve may be called into operation or may operate within each value of the foreseen ranges.

The selected critical parameters, which complete the identification of the system configuration during its mission, are reported in Table 2, together with the proposed discrete ranges of variation.

Table 2 – Critical parameters of the passive system.

Critical Parameter		Discrete Values						
x_1	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***
x_2	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	0.		1.		5.		10.
		0.5		***0.4***		***0.08***		***0.02***
C_2	Heat Losses piping – IC Suction (kW)	0.		5.		20.		100.[4]
		0.10		***0.7999***		***0.10***		***0.0001***
$L_2(0)$	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***

As in the previous table, a probability is arbitrarily assigned to each discrete value. The considered values could be the result of a PSA evaluation or based on engineering judgement.

It might be noted that the combination of all discrete values in Tables 1 and 2 brings to a several million initial status for the system. Therefore, a statistically meaningful selection of initial status is necessary.

4 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.

The following quantities (ref. Figure 1) are assumed to be strictly connected with the acceptability or design limits of the system and are the output of the reference code calculation:

a) Thermal power exchanged across the IC (W_2)
b) Mass flowrate at the IC inlet (Γ_2)

A unique failure criterion is defined as a function of time:

$$(Z - Z_{ref}) / Z_{ref} < (-0.2) \qquad (1)$$

where Z may be either W_2 or Γ_2 and "ref" is related to the reference code calculation.

The condition (1) has to be continuously valid for a time interval greater than 100 s.

The following indicators are defined for the evaluation of system performance:

1) Failure time, that is time during the calculation when the condition (1) is verified;
2) Ratio Y/Y_{ref} , where Y is the integral of W_2 and of Γ_2 performed between time 0 (start of the system operation) and the time of the calculation end.

5 SYSTEM ANALYSIS RESULTS

One-hundred-forty-four (144) system status, constituting two ensembles of system status, have been selected according to deterministic and statistic choice (both via discrete and continuous probability distribution) and have been associated to individual code runs.

Six system status, shown in Table 3, have been selected deterministically in order to get the sensitivity in relation to the effect of each relevant parameter, and not with the purpose to bound the results expected from the statistically based selection.

Table 3 – System status deterministically selected

No	Main Parameter Studied	P_1	L_1	L_3	$T_p(0)$	System Geometry	x_1	x_2	θ	C_2	$L_2(0)$	UL	POV	Prob.ty
1	Nominal conditions	7	8.7	4.3	303	Nominal	0.	0.	0.	5.	100.	0.	100.	*2.06E-2*
2	Pressure & Level	0.2	12	4.3	303	Nominal	0.	0.	0.	5.	100.	0.	100.	*6.20E-4*
3	Gas	7	8.7	4.3	303	Nominal	0.01	0.5	0.	5.	50.	0.	100.	*1.82E-5*
4	Leakage	7	8.7	4.3	303	Nominal	0.	0.	0.	5.	100.	5.e-5	100.	*2.32E-4*
5	Valve	7	8.7	4.3	303	Nominal	0.	0.	0.	5.	100.	0.	10.	*2.32E-4*
6	'Extreme'	0.2	5	2	368	Nominal	0.01	0.5	0.	20.	0.	1.e-5	50.	*4.5E-12*

Two random selections of sixty-nine system status based on discrete and continuous probability distributions have been set up for evaluating the influence of probability distributions upon the calculated system performance.

Therefore, 144 code runs have been performed, each one lasting 15000 s simulated time and requesting about 20 hrs of execution time. The transient operation starts with the valve opening.

The indicators of system performance have been applied separately to the two ensembles of seventy-five (75) system status obtained by summing up the six 'deterministic' status and each set of sixty-nine 'statistic' status.

The results per each ensemble of 75 code runs are reported in Figures 2 to 5. The Figures 2 and 3 show the system failures and success fraction obtained from discrete and continuous probability distributions, whereas the Figures 4 and 5 report the IC power integral ratio in the case of discrete and continuous distribution.

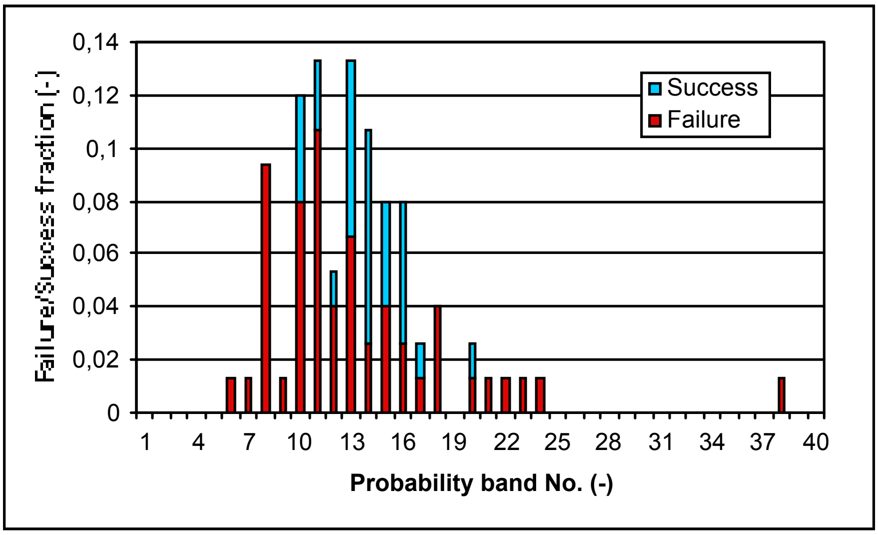

Figure 2 : Failure/success fraction as a function of the probability of the status in the case of discrete probability distribution.

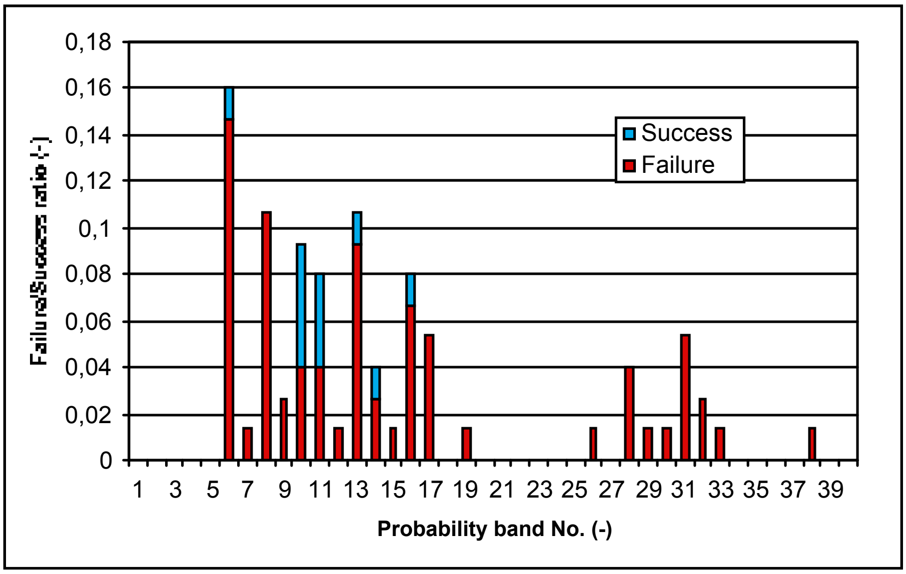

Figure 3 : Failure/success fraction as a function of the probability of the status in the case of continuous probability distribution

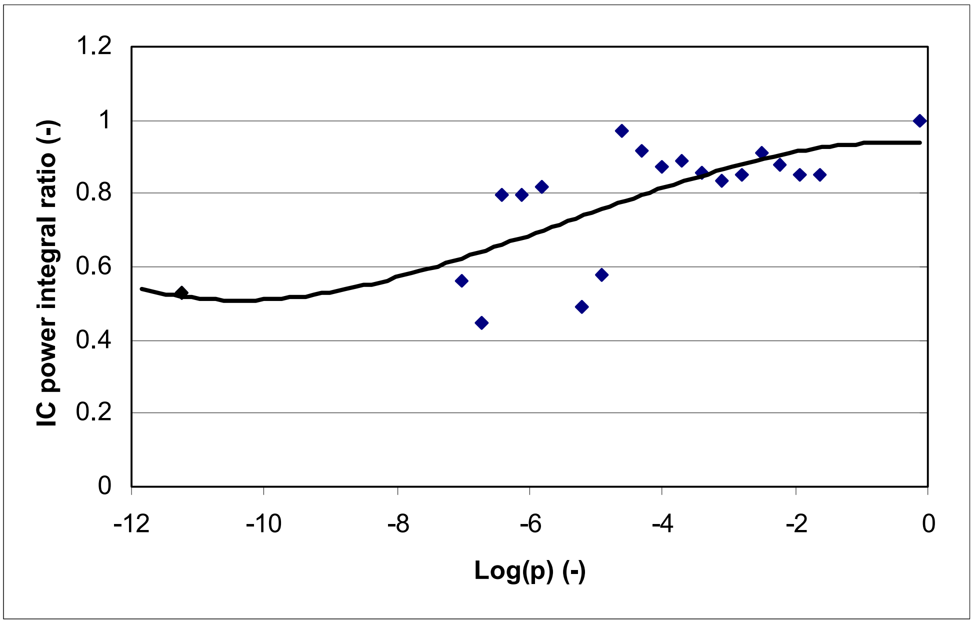

Figure 4 : Probability distribution for the performance indicator 'IC power integral ratio' in the case of discrete probability distribution.

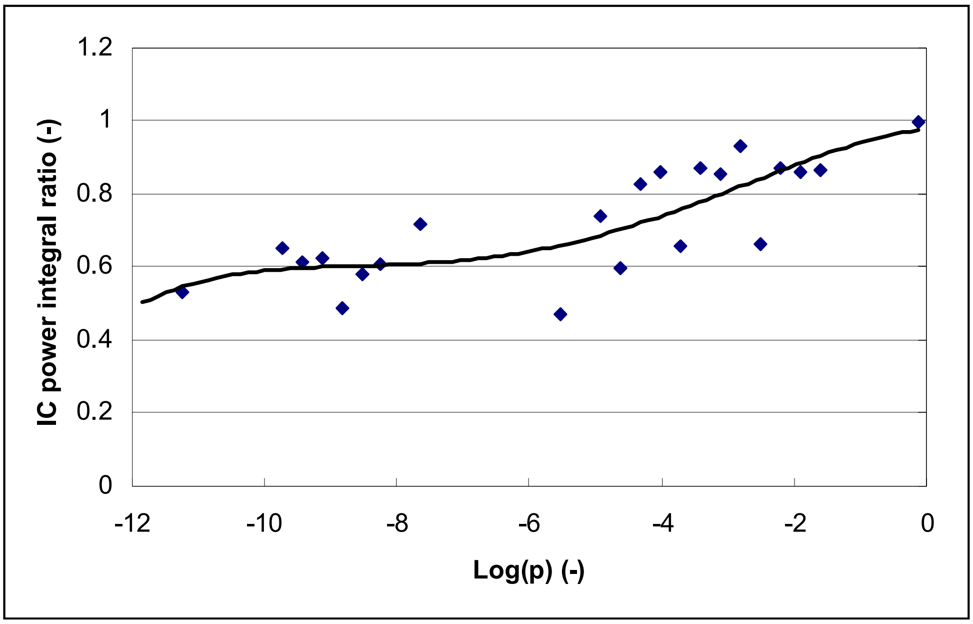

Figure 5 : Probability distribution for the performance indicator 'IC power integral ratio' in the case of continuous probability distribution.

7 CONCLUSIONS

The analysis of the results shows that the procedure is available to evaluate the performances of a passive system and can be applied: 1) for evaluating the acceptability of a passive system, specifically when nuclear reactor safety considerations are concerned; 2) for comparing two different passive systems having the same mission; and, with additional investigation: 3) for evaluating the performances of an active and a passive system on a common basis.

Limitations of the achieved results and areas for further development or improvements of the procedure have been identified and can be summarized as follows:

a) Reference system performance must be selected as nominal behaviour of the system, corresponding to the ideal fulfilment of its mission. This must be available to the analysts that are user of the procedure. The system code may be utilized to confirm this target. This implies that the designers of the system are involved in the application of the procedure.
b) More rigorous and systematic basis is necessary to select the parameters that characterize the system status. The independence of results upon a minimum number of selected parameters should be demonstrated.
c) The number of considered combinations (i.e. the number of code runs) should also be defined in such a way to ensure the convergence of the results (i.e. judgement of system performance) when the same number is increased.
d) In the present contexts, the thermal-hydraulic system code has been considered as an ideal tool, perfectly reproducing the real physical behaviour of the whole system. Uncertainty in the predictions should be added in the analysis.

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