6th International Conference on Nuclear Engineering
ICONE-6340
May 10-14, 1998

RELIABILITY ASSESSMENT OF PASSIVE SAFETY SYSTEMS

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ABSTRACT

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 component 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. Besides the open feedback on economic competitiveness special aspects like lack of data on some phenomena, missing operating experience over the wide range of conditions and the smaller driving forces as - in most cases - compared to active safety systems must be taken into account. Both for active and passive systems, the effective reliability versus the achievement of safety functions is considered as an essential criteria for judging the real potential of the systems.

Generally speaking, the reliability assessment of passive safety functions defined as the probability to fail the requested mission to achieve a generic safety function, depends, more than for active systems, on environment, physical, nuclear or chemical phenomena.

This remark is entirely applicable to the passive B systems (i.e. implementing moving working fluids, cf. IAEA). Their mission is defined through a nominal requested time dependent evolution, for a set of selected and representative parameters and an allowable range is allocated around the nominal evolution.
It is stated that the mission fails when the plant parameters are outside the allowable range.

As a first approach, it is considered that the reliability assessment of passive safety functions can be estimated evaluating the probability for having the mission failure. This assessment is achieved comparing the distribution of the expected parameters values to the allowable range.

This implies the identification and quantification of the uncertainties in the prediction of physical phenomena performances or interdependencies. In parallel, an adequate effort must be devoted to the improvement of thermalhydraulic computer codes that model the passive safety system behaviour to integrate those uncertainties. Finally, the transfer of the structural methodology assessment methodology (i.e. for passive A systems) must be checked to verify its applicability for the thermalhydraulic passive systems, too.

The paper is focused particularly on passive B safety functions and related systems and illustrates a possible methodology for their reliability assessment.

The example explained in the report can be used as a preliminary basis to motivate and to organise the content of a work that could be conducted within the framework of the European Commission sponsored activities on Reliability Methods for Passive Safety Functions.

INTRODUCTION

In the recent years an important effort has been made by suppliers, industries, utilities and research organisations on passive safety systems both for their development and assessment.

Within this context it is essential to account also for the passive features in the plant safety analysis particularly in the accident sequence definition and finally in the probabilistic risk assessment studies. Consequently the reliability assessment of passive safety functions defined as the probability to fail the requested mission, becomes an essential step.

A passive system should be theoretically more reliable than an active one. The reasons are that it does not need any external input or energy to operate and it relies only upon natural physical laws (e.g. gravity, natural convection, conduction, etc.) and/or on inherent characteristics (properties of materials, internally stored energy, etc.) and/or 'intelligent' use of the energy that is inherently available in the system (e.g. decay heat, chemical reactions etc.).

Nevertheless passive devices can be subject to specific kinds of failure like, e.g., structural failure, physical degradation, blocking.

Generally speaking, the reliability of passive systems depends upon:

- the environment that can interfere with the expected performance,
- the physical phenomena that can deviate from the expectation,
- the single components reliability.

Previous references already discuss the corresponding general issues. The principle of this mutual interaction is showed in the first figure.

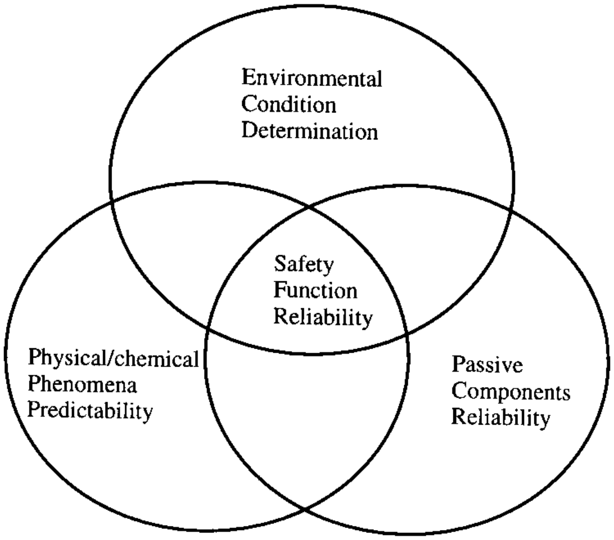

Fig. 1 - Parameters affecting the functional reliability

This paper reports a survey on the type B passive functions, the related systems and the plausible failure modes. A possible methodology for the reliability assessment is discussed.

Finally the application of this methodology to the safety passive functions involved is shown.

SURVEY ON PASSIVE SAFETY SYSTEMS AND PASSIVE SAFETY FUNCTIONS

Following the IAEA definitions (ref. 1) a passive component does not need any external input to operate. The term "passive" identifies a system which is composed entirely of passive components and structures or a system which uses active components in a very limited way to initiate subsequent passive operation. A categorisation has been developed by the IAEA (mainly on the background of thermalhydraulic safety systems) distinguishing:

A: physical barriers and static structures,
B: moving working fluids,
C: moving mechanical parts,
D: external signals and stored energy (passive execution/active actuation).

As suggested by the ref. 1, this contribution uses similar categories to characterise the means by which a safety function (a physical, neutronic or chemical effect) is achieved in a more general way:

A: by structure through material choice and material condition, design, and geometrical arrangement,
B: by moving fluids and gases, by phase changes, by chemical reactions, and by coupled neutronic effects,
C: by moving mechanical parts,
D: by using stored energy (passive execution/passive or active actuation).

This paper is focused on the analysis concerning the type B functions which, for example, provide the Decay Heat Removal safety mission.

“RELIABILITY ASSESSMENT OF PASSIVE SAFETY FUNCTIONS”: GENERAL APPROACH AND METHODOLOGY

For the reliability assessment of passive safety functions of B, C and D type there is the need to integrate the ‘chain’ of functions requested to achieve a given mission.

Each element of the ‘function chain’ either reinforcing each other, or depending on each other, have to be assessed separately under a consistent probabilistic methodology.

The mission is defined through a nominal requested time dependent evolution, for a set of selected and representative parameters. An allowable range is allocated around the nominal evolution (see fig. 2).

It is stated that the mission fails when the plant parameters are outside the allowable range.

As a first approach, it is considered that the assessment of the reliability of the passive function can be achieved evaluating the probability for having the mission failure.

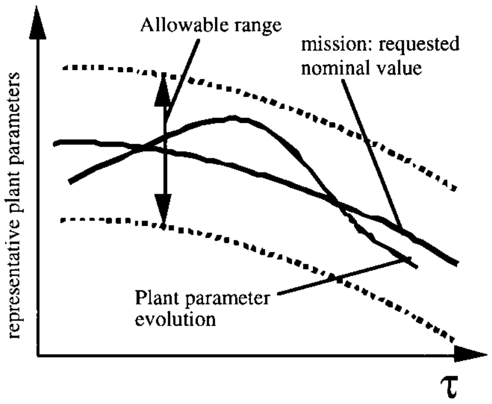

Fig. 2 - Allowable mission for a passive system

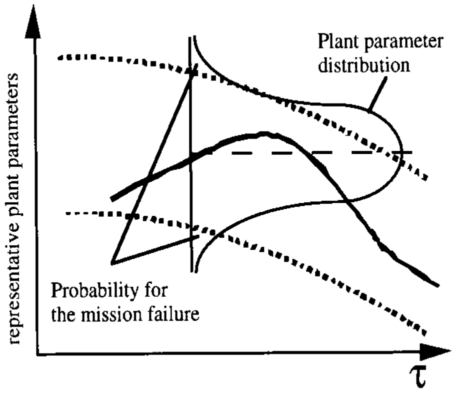

Fig. 3 - Mission failure for a passive system

As for the structural reliability analysis, the quantification of this probability is achieved comparing the distribution of the expected parameters values to the allowable range (see figure 3).

The authors suggest several steps to structure the work (see ref. 2):

- *Identification of the parameters that characterise the generic missions and of the criteria that define their failure. Review of the correlations, data, and codes needed for the deterministic description of the missions, and their failure versus the identified criteria, taking into account all the important parameters. Identification of the eventual needs for improvement.*
- *Identification of the sources of uncertainties of the parameters. Review of the existing computer programs to integrate them within the missions description, either for the success or for its failure. Identification of the eventual needs for improvement.*
- *Review of the tools for functional reliability analysis (the functional reliability is defined as the probability of the mission failure). Identification of the eventual needs for improvement of tools.*
- *Identification of specific inspection and maintenance techniques and procedures.*
- *Consideration of interaction between the human actions or activities and the systems/features functional reliability. If possible, implementation within the functional reliability tools.*
- *Collection, comparison and exchanges on operating experience.*
- *Performance of several examples of functional reliability analysis with sensitivity studies on selected passive systems.*

The report relates with the first three steps through an application to Decay Heat Removal (DHR) systems.

FAILURE MODES IN THE PASSIVE FUNCTION PERFORMANCE

In the above mentioned report (ref. 2) the generic failure modes are correlated to several passive systems currently designed for the innovative plants. The table below shows the same correlations in a more general way.

Table I Failure mechanisms and corresponding consequences for passive safety functions and related passive safety systems

Failure mode	Consequences	Safety function involved	Passive Safety System
envelope failure	leak (flow rate reduction)	DHR	Natural Circulation System
friction (check valve involved)	rubbing (movement reduction)	DHR	Passive Core Cooling System
stratification	reduction of heat convection	DHR	Natural Circulation System
presence of non condensables	reduction in heat exchange efficiency	DHR	Natural Circulation System
boron concentration modifications	reduction in reactivity worth	RC	Boron Injection
modification of the surface characteristics (e.g. oxidation)	reduction of heat radiation	DHR	Containment Natural Heat Removal
cracking 1	reduction of heat conduction	DHR	Natural Circulation System
cracking 2	leakage	FPC	Containment Building
blockage	flow rate reduction	DHR	Natural Circulation System
deposits	reduction of heat transmission	DHR	Natural Circulation System
chemical deactivation	reduced chemical reactions	H2R	Catalytic Hydrogen Recombiners

Legenda: DHR Decay Heat Removal, FPC Fission Product Confinement,
RC Reactivity Control, H2R Hydrogen Removal

In the following chapters some of the above failure modes, together with the related causes, are exemplarily taken into account in order to provide a methodology for the assessment of the reliability of passive systems, focusing on the Natural Circulation relying systems.

PROBABILISTIC METHODS FOR THE ASSESSMENT OF SAFETY FUNCTION RELIABILITY

The qualitative concept of reliability assessment of passive safety functions has been introduced above. The quantitative assessment is achieved (ref. 2 and 3) by the introduction of the limit state function g(x) taken from the general reliability theory and defined as:

$$g(x) = r(x)-s(x) \qquad \begin{cases} > 0 \text{ for safe function} \\ = 0 \text{ at limit state} \\ < 0 \text{ for mission failure} \end{cases} \qquad \text{(Eq. 1)}$$

r(x) functional requirement (plant parameter, e.g. temperature, pressure, requested value)
s(x) system state (“operating” plant parameter)

In the probabilistic model ‘r’ and ‘s’ are defined as the probabilistic density functions which depend on several basic variables x affected by the uncertainties (e.g. geometric and material properties, physical quantities, etc.). The characteristic parameters for the probabilistic distribution are represented, e.g. for the ‘normal distribution’, by the mean value and the variance.
In the following chapters the foregoing methodology is being applied to the Safety Functions in a qualitative way evaluating the single failure probability distributions related to the various failure modes and combining them in order to finally evaluate the overall system failure probability.
In the weakest-link model the system failure probability and reliability can be expressed respectively by the expressions (ref. 3):

$P_t = 1- \Pi_i (1-P_i)$, where P_i is the failure probability for each failure mode (Eq. 2)
$R_t = \Pi_i R_i$, where R_i is the single reliability related to every failure mode (Eq. 3)

TYPE B PASSIVE SAFETY SYSTEM RELIABILITY EVALUATION

As stressed in section 3, the « reliability assessment of passive safety functions » needs to evaluate simultaneously a « chain » of passive functions. For example, for the passive DHR the following items shall be considered:

• Fluid envelope integrity	type A
• Heat conduction through material thickness (e.g. tube)	type A
• Heat transfer by fluid convection	type B

and if foreseen :

• Valve opening/closing	type C
• Electrical impulses	type D

It is well understood that the failure of one of these components can strongly affect the achievement of the required mission. For example the type A functions (i.e the heat conduction and the structural integrity) strongly affect the type B safety functions in achieving the required mission and can be considered a preconditon for additional thermalhydraulic analysis.

In this treatment first of all one recalls any principles on which the free convection cooling is based.

Natural Convection Cooling

In natural convection the motion is a consequence of the buoyant forces generated in the fluid due to temperature differences within it, (ref. 4).

If p_1 and p_2 are the densities of the coolant at entrance and discharge, respectively, from the convective cooling channel, the pressure differential, i.e. the driving force, is approximately

$$\Delta p = (p_1 - p_2)gL \qquad \text{(Eq. 4)}$$

where g is the acceleration of gravity and L the length of the tube.

The flow in natural convection regime can be considered approximately laminar because of the low heat flux and the consequent small convective driving force.

The flow rate and, hence, the ability to carry heat from the core by natural convection alone may be estimated in the following manner.

The pressure drop Δp accompanying isothermal laminar flow at a mean velocity u in a cylindrical pipe of diameter D and length L is given by the familiar Poiseuille equation:

$$\Delta p = 32\mu uL/D^2 \tag{Eq. 5}$$

where μ is the viscosity.

For convective cooling, u in equation 5 will then be the average upward velocity of the coolant when pressure drop Δp is equal to the average pressure drop due to difference in density at bottom and top.

The average velocity of the fluid is obtained equating Eq. 4 and Eq. 5, that is:

$$u_{av} = (p_1 - p_2)g\,D^2/32\mu_{av} \tag{Eq. 6}$$

where μ_{av} is the average viscosity.

The total rate of heat removal from the channel in natural convection q is equal to the product of the mass flow-rate w of the coolant, its specific heat c_p and the average raise ΔT that is:

$$q = w\,c_p\Delta T \tag{Eq. 7}$$

Since w may be replaced by upA_f, where A_f is here the total flow area, it follows that

$$q = (p\,c_p)\,u\,A_f\,\Delta T \tag{Eq. 8}$$

In the present case u is given by Eq. 6, p is the mean density, i.e. $1/2(p_1 + p_2)$ and ΔT is t_2-t_1, the temperature difference between the top and bottom of the channel. Hence Eq. 7 becomes:

$$q = (p_1 + p_2)(p_1 - p_2)\,A_f\,g\,D^2\,c_p\,(t_2 - t_1)/64\,\mu_{av} \tag{Eq. 9}$$

which may be used to estimate the power removal capability for specified lower and upper temperatures and can be taken as reference parameter for the following analysis.

In this theoretic treatment any effects that can be significant, including pressure losses due to flow area variations (e.g. pressure losses at the pipe inlet and discharge), deviations from laminar flow and nonuniform surface temperatures, have been neglected.

Failure Modes and Uncertainty Identification

The failure modes whose consequences can affect the heat removal by natural circulation are identified according to table I as the following:

- envelope failure due to abnormal stresses, localized stresses, ageing effects (e.g. embrittlement), material defects, welded joint defects, corrosion: as previously indicated this is a type A system failure which causes cooling liquid leak, consequent flow rate reduction and hence lesser heat removal capability.
- cracking due to material defects, welded joint defects, localized stresses, corrosion: this failure mode interests the type A system (pipe wall) and results in reduction of heat conduction and hence lesser heat removal capability.
- modification of surface characteristics (e.g. oxidation, deposits) which results in reduction in heat exchange efficiency.
- thermal stratification: this results in reduction of heat convection.
- presence of non-condensables: the consequence is a reduction in heat exchange efficiency.
- friction, i.e. rubbing (movement reduction), which can lead to blockage of valves (if foreseen), and consequently flow rate reduction and therefore natural circulation stop.

A lot of uncertainties are associated with the natural circulation: the first source of uncertainties concerns the individual phenomena in the context of the failure modes and related consequences described above.

In thermalhydraulic analysis various parameters are influenced by uncertainties to be taken into account and reliability methods employ two values for each uncertain parameter (commonly mean value and variance).

Up to now the codes used in thermalhydraulic analysis, like RELAP and CATHARE, are “best estimate” codes which don’t account for the uncertainties in their correlations and have deficiencies in modelling the important physical phenomena involved which determine, e.g., the natural circulation flow behaviour. Hence, probabilistic thermalhydraulic codes have to be developed for a quantitative reliability assessment of passive B type safety systems.

The main uncertainties arise from the the correlations -analytical and/or experimental - used to describe the physical phenomena: let us consider the heat transmission by convection mechanism and the correlation

$$q = h\ A\ \Delta T \qquad \text{(Eq. 10)}$$

in which q is the rate of convection heat transfer from the surface of area A, when the temperature difference is ΔT and h is the commonly called heat-transfer coefficient.

The coefficient h, although it is dependent upon the physical properties of the fluid medium, is function of the shape and dimensions of the interface and of the nature, direction and velocity of the fluid flow. Thus the heat-transfer coefficient is a property of the particular system under consideration. Another factor which determines h is the exact definition of “Delta T”, i.e. the temperature difference between the surface and the fluid. Summarizing the coefficient h is subject to uncertainties regarding geometric properties, material properties and physical parameters. Similarly the heat exchange surface area depends upon geometric characteristics and dimensional values and the temperature values are not the real but the mean values of the surface and coolant temperature which are considered constant, while, in reality, there is a continuous fluctuation in a certain range.

Analogously, the same considerations are valid for almost all the thermalhydraulic correlations for whom either the coefficients (heat transfer coefficient, thermal conductivity coefficient, friction factor), or the physical quantities and parameters (e.g. pressure, temperature, mass flow, etc.) are respectively affected by uncertainties or are fluctuating during the reactor operation.

In the frame of the thermalhydraulic analysis, indeterminations concern also the above considered failure modes and related causes and consequences such as leaks (e.g. from pipes, pools, etc.), deposit thickness (e.g. on pipe surfaces, etc.), presence of non-condensable gases, stresses, blockages (valves, if foreseen) and material defects.

Other sources of uncertainties are mainly due to environmental attacks, e.g.:

- internal and external incidents (temperature, pressure, loads, cooling inventory)
- ageing effects (creep, fatigue, corrosion)
- impurities (gases, liquids, solids)
- corrosion products
- fission products
- radiolysis products
- coolant chemistry (pH, O_2, H_2, boron, etc.)
- irradiation effects.

The foregoing factors may be accounted for individually or better as a boundary event combination (e.g. effect sum of deposits, non-condensable gases, leaks) leading to the passive function failure: in every case they determine the performance of the systems based on natural circulation. Some of those DHR systems are presently under development, eg. Emergency Condenser (ref. 5) and Thermal Valve (ref. 6).

Major points of tests and analysis to be performed in order to assess the heat removal by natural circulation and to reduce the related uncertainties should be focused on:

- the heat transfer coefficient of the heat exchangers (e.g. isolation condenser, which are foreseen to be submerged in a cooling pool): for the design of the bundle of the heat exchanger the provisions to reduce the thermal resistance of the wall and increase the heat coefficient transfer (this means a reduction of the heat transfer surface and possibilities for leakages) are the reduction of the tube wall thickness and the use of material with higher thermal conductivity. This may collide with the desirable increase of the inner diameter of the tube for limiting the pressure losses caused by the higher mass flow.

- the flow stability through the natural circulation circuit: this problem can be evaluated by code calculations. As already stressed they need to be developed in the modelling of the passive system behaviour like natural convection.

Natural Circulation Failure Probability

For the assessment of the natural circulation failure probability distribution the required parameters are the mean heat removal power value, see Eq. 9, and the variance that represents the uncertainty associated with the mean value, i.e. either the random uncertainties in material and geometric properties and in the chemical/physical phenomena which affect the thermal hydraulic behaviour or the uncertainties linked to the thermalhydraulic correlations.

The critical value of heat removal power may be defined as that value of the heat flux q for which the mission fails: according to fig. 2, there are an upper and lower critical value of the heat flux above and below which, respectively, the mission fails, i.e. the system based on natural circulation is not able to remove the reactor core decay heat.

It has to be noted that the evaluation of the natural circulation from the probabilistic point of view can focus also on other relevant parameters that can be chosen among the following:

- coolant fluid temperature
- convection heat flux (i.e. heat transfer between surface and fluid)
- temperature difference between fluid and surface in case of the presence of a heat exchanger
- mass flow.

Based on the uncertainties defined above and the mean value represented by the best estimate value of the actual heat flux under the various failure modes (estimated from the results of the thermalhydraulic codes) the statistic distributions which would be suitable to describe the failure probabilities for each failure mode can be constructed.

The Natural Circulation failure distribution is constructed by assuming that all of the uncertainties and all of the failure modes are independent of each other. That is, the Natural Circulation failure probability distribution for a particular failure mode (e.g., presence of non-condensables) is constructed by developing the failure distribution assuming only random error and then developing another distribution assuming only correlation related error. The two probability distributions are then combined to define the Natural Circulation failure probability distribution for that particular failure mode. This process is carried out for each failure mode and the overall Natural Circulation failure probability distribution is defined by combining the failure probability distributions for each failure mode.

The failure probability distributions are combined at any given heat flux by summing the probability of failure at that heat flux for each distribution in order to assess the cumulative Natural Circulation failure probability according to Eq. 2:

$$Pe_t = 1.0- ((1.0 - Pe_1)*(1.0 - Pe_2)*...*(1.0 - Pe_n)) \qquad \text{(Eq. 11)}$$

where: Pe_t = overall probability of failure at any heat flux

Pe_1 through Pe_n = individual probabilities of failure at any heat flux

The single values concerning the individual probabilities of failure at any heat flux are computed according to:

$$Pe = \int_{g(x)\leq 0} f_x(x)\,dx \qquad \text{individual probability of natural circulation failure} \quad \text{(Eq.12)}$$

where $g(x) = Q_r - Q_s$ Q_r = critical heat flux
Q_s = actual heat flux in irregular conditions

$f_R(Q_r)$: probability density function of Q_r
$f_S(Q_s)$: probability density function of Q_s
$f_X(x)$: joint probability density function of the basic variables x
$g(x)$: limit state function corresponding to the safety margin $M = g(x)$

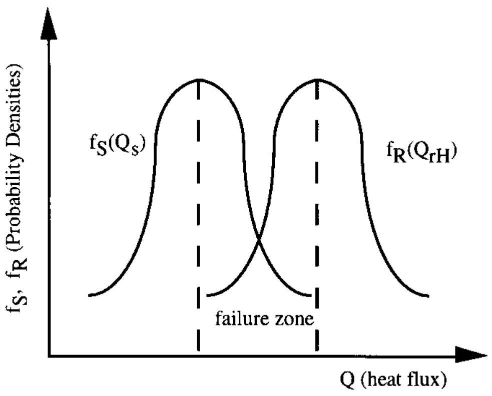

Fig.4 - Heat flux probability density function - Failure Mode for the upper critical heat flux Q_{rH}

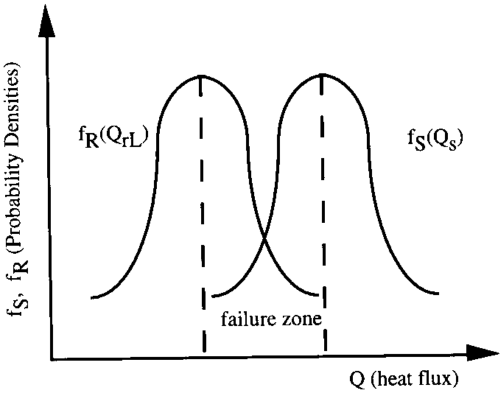

Fig.5 - Heat flux probability density function - Failure Mode for the lower critical heat flux Q_{rL}

As seen, this methodology is quite similar to the stress-strength model and the safety margin concept (see Eq. 1), with the introduction of the probabilistic distributions of Q_r and Q_s relative respectively to the design requirement and the system state: there is however a subtile difference. In fig. 4 any s > r contributes to the failure probability Pe. It shows the situation for failures by exceeding the allowable range ($Q_r = Q_{rH}$). According to fig. 2, there is yet another failure mode of the plant parameter falling below the allowable range. In this case the limit state function becomes $g(x) = Q_s - Q_r$ with $Q_r = Q_{rL}$, (see fig. 5). The total failure probability is obtained from the two failure modes by Eq. 2.

In conclusion the Natural Circulation failure probability distribution has been developed in terms of the heat flux using an appropriate distribution for each of the failure modes: based on this model the mean heat flux at which the natural circulation is predicted to fail can be evaluated.

CONCLUSIONS

A methodology for the evaluation of the probability distribution of passive B safety functions has been proposed for the natural circulation relying systems.

First of all the main failure modes have been identified based on the examination of the natural convection stability. Each of the failure mode is then examined to determine the best estimate of the mean critical heat flux. Concerning the correlations utilized to carry out the thermalhydraulic analysis, the random and model uncertainties associated with each of the failure modes are identified.

These failure characteristics are then used and combined to develop a probabilistic model to predict the natural circulation failure due to insufficient heat removal capability.

The further step in the reliability assessment of passive systems is the application of the foregoing methodology to an actual passive system, presently in progress, which can be identified among the following: emergency condenser, thermal valve, etc.: for them a detailed study is intended to be performed, the probabilistic parameters (i.e. the mean value and the variance) will be quantified in order to finally assess the reliability: this task seems to be very difficult because it implies, among others, thermalhydraulic analysis and the development of mathematical models for passive component reliability; besides many deficiencies still exist in the understanding and modelling the phenomena affecting the passive systems and test programs must be defined in order to quantify and reduce the corresponding uncertainties.

Finally an effort has to be devoted to the development of the thermalhydraulic codes which must account for both the uncertainties in their correlations and the phenomena which determine the natural circulation failure.

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