Summary of the Activities and main Achievements in IAEA CRPI31018: "Development of Methodologies for the Assessment of Passive Safety System Performance"

D. Araneo, A. Raimato, V. Cefalì, F. D’Auria
GRNSPG - Gruppo di Ricerca Nucleare San Piero a Grado University of Pisa
Via Livornese 1291, San Piero a Grado, Pisa, Italy
d.araneo@ing.unipi.it, alfredo.raimato@dimnp.unipi.it, vincenzo.cefali@dimnp.unipi.it,
dauria@ing.unipi.it

L. Burgazzi
ENEA Bologna
Via Martiri di Monte Sole 4, Bologna, Italy
burgazzi@bologna.enea.it

M. Bykov
Gidropress Podolsk
Ordzhnikidze ulitsa 21, Podolsk, Moskovskaya Oblast, Russian Federation
bykov@grpress.podolsk.ru

M. Marques
CEA Cadarache
ST. Paul Lez Durance, France
michel.marques@cea.fr

J. Arul, U. P Sarathy
IGCAR, NSEG Thermal Hydraulic Section
Kalpakkam 603 102, India
john_arul_a@yahoo.co.in, ups@igcar.gov.in

V. Jain
BARC Trombay
Mumbay, Maharashtra 400 085, India
jainv@barc.gov.in

M. Giménez
CNEA Bariloche
Avenue Bustillo Km 9-5 San Carlos de Bariloche, Argentina
 gimenez@cab.cnea.gov.ar

B. G. Williams
ISU
College of Engineering, Campus Box 8060
Pocatello, ID 83209, Idaho, USA
willbria@isu.edu
One of the main concerns for the safety of the nuclear power plant is the possibility to rely on systems that do not need any external source of energy or operator action. Such passive systems can potentially lead to an increase in the safety level of the plant and to a reduction of the cost for energy production. The passive safety systems for their nature, because their functioning depends only by natural physical law, are more reliable than the active ones. Nevertheless, the passive systems may fail in their mission as consequences of components failure, deviation of physical phenomena, boundary and initial conditions, etc.

Because of these events, the need of a deep evaluation of their reliability is a mandatory task. Different methodologies have been proposed in literature for the evaluation of the reliability of passive and active safety systems within a common PSA (Probabilistic Safety Assessment) approach. What is important from the perspective of the overall risk assessment is that these methodologies take into account uncertainties associated with unforeseen physical phenomena that may affect the operation of passive systems, worsening their reliability. All of the methodologies are at a preliminary stage of development and no consensus on a common approach has been established so far among their proponents.

In this direction IAEA has launched the CRP-I31018 (Coordinated Research Project) on 2009 and in phase of completion at the end of 2011. This CRP aims on development of a common approach to assess performance of passive safety systems. Such an approach could facilitate design optimization and safety qualification of the future advanced reactors, contributing to their enhanced safety levels and improved economics. Moreover, the project is expected to pool together efforts of all principal developers of the relevant approaches and methodologies worldwide, and also to attract capable new participants.

Three methodologies have been considered: REPAS (Reliability Evaluation of Passive Safety System), RMPS (Reliability Method for Passive System), APSRA (Assessment of Passive System Reliability).

In this paper, the main activities carried out during the 2 and half years are described together with the planned ones for the remaining half year.

One of the main outcomes of this CRP-I31018 is the first attempt to qualify the selected methodologies for reliability analysis of passive safety systems against data coming from an experimental test facility: a vertical, square shaped natural circulation loop, filled with water, working at atmospheric pressure. The natural circulation is generated by heating the lower horizontal tube (heat source) and cooling the upper horizontal tube (heat sink). Because of the simplicity of such system, there is the possibility to control each parameter that affects the performance of the natural circulation phenomenon.

A test matrix has been developed with the aim to observe experimentally the transition from unstable/stable natural circulation once the power at the heat source is fixed and the temperature at the heat sink is changed and kept constant during each transient.

The basic idea followed in the qualification strategy is that the reliability observed experimentally has to be compared with the calculated one by the applied methodologies.
1 INTRODUCTION

The expanded consideration of severe accidents, the increased safety requirements, and the aim of introducing effective - yet transparent - safety functions lead to growing consideration of passive safety systems for future nuclear reactors.

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 [1], 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.

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.

This remark is especially applicable to the passive systems B or C (i.e. implementing moving working fluid, following IAEA classification1 [1]) and in particular to the passive systems that utilize Natural Circulation (NC). These passive safety systems in these designs rely on natural forces (i.e. 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 in usually done with pumped systems.

Moreover, there are considerable uncertainties associated with factors on which the magnitude of these forces and counter forces depends (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 this reason, the reliability of the systems that utilize NC must be assessed.

A methodology for reliability assessment of passive safety systems would enable quantification of the reliability to treat both active and passive safety systems within a common PSA approach. Several such methodologies are under development in Europe, India, and the USA [2][3]and [4]. What is important from a perspective of the overall risk assessment, these methodologies take into account uncertainties associated with unforeseen physical phenomena that may affect the operation of passive systems, worsening their reliability. All of the methodologies are at a preliminary stage of development and no consensus on a common approach has been established so far among their proponents.

As an example, in the late 1990s, a methodology known as Reliability Evaluation of Passive Safety System (REPAS) was developed cooperatively by ENEA, the University of Pisa, the Polytechnic of Milan and the University of Rome [5] in Italy that was later incorporated in the European Commission’s Reliability Methodology for Passive Systems (RMPS) project within the EC’s 5th Framework programme [6][7]. The RMPS methodology is based on the evaluation of a failure probability of a system to carry out the desired function for a given set of scenarios taking into account the uncertainties of those physical (epistemic) and geometric (aleatoric) parameters the deviations of which can lead to a failure of the system. The RMPS approach considers a probability distribution of failure (pdf) to treat variations of the comparative parameters considered in the predictions of codes.
A different approach followed is the “APSRA” methodology developed at BARC, India. In this approach, the failure surface is generated by considering the deviation of all those comparative parameters which influence the system performance. Then, the causes of deviation of these parameters are found through root diagnosis. It is attributed that the deviation of such physical parameters occurs only due to a failure of mechanical components such as valves, control systems, etc. Then, the probability of failure of a system is evaluated from the failure probability of these mechanical components through classical PSA treatment. Moreover, to reduce the uncertainty in code predictions, BARC makes use of the in-house experimental data from integral facilities as well as separate effect tests.

During a dedicated IAEA technical meeting of 12-16 June 2006, held with broad representation of interested stakeholders, it was noted that APSRA and RMPS are complementary in the following:

- APSRA incorporates an important effort on qualification of the model and use of the available experimental data. These aspects have not been studied in RMPS, given the context of this project;
- APSRA includes in the PSA model the failure of those components, which cause a deviation of the key parameters resulting in a system failure, but does not take into account the fact that the probability of failure of a physical process could be different from unity.
- RMPS proposes to take into account in the PSA model the failure of a physical process. It is possible to treat such data (best estimate code plus uncertainty approach is suitable for this purpose).
- In fact, two different philosophies or approaches have been used in RMPS and APSRA, and the two developed methodologies are, therefore, different. At the same time, one of the efforts of this CRP is to analyse the possibility that certain parts of the APSRA and the RMPS could be merged in order to obtain a more complete methodology.

2 CRPI31018 STRUCTURE AND OBJECTIVES

The CRPI31018 implements the programmatic activity of the IAEA sub-programme 1.1.5 “Technology Development for Advanced Reactor Lines” and the IAEA project 3.2.3.3 “Fostering technical developments and trends in safety analyses”, starting with the IAEA Program for the period 2008 – 2009. The sub-programme 1.1.5 has the objective to achieve progress in the development of advanced nuclear power technologies that have competitive economics and meet stringent safety objectives through international information exchange and coordinated research, and the Project 3.2.3.3 has the objective to facilitate, among others, technical developments of new trends and issues in safety analyses, and to share with Member States.

The objective is to determine a common method for reliability assessment of passive safety system performance. Such a method would facilitate application of risk-informed approaches in design optimization and safety qualification of the future advanced reactors, contributing to their enhanced safety levels and improved economics.

The scope of the problems associated with further development of methodologies for reliability assessment of passive safety systems was elaborated at the IAEA technical meeting “Status of Validation and Testing of Passive Safety Systems for Small and Medium Sized Reactors (SMRs)” held in Vienna on 12-16 June 2006 and through direct communications with the developers of such methodologies. In line with these discussions, the specific research objectives of this CRP are:

- Identify requirements for a method of reliability assessment of passive safety systems for future advanced NPPs;
• Work out a set of definitions for reliability assessment of passive safety systems and
their treatment by PSA, e.g., ‘reliability of a passive safety system’, ‘safe end state’ of
accident sequences, ‘mission time’, etc. (a consensus should also be reached on whether
proving the ability of passive systems to perform their function is clearly related to the
selection of a certain PSA modelling approach);
• Identify a benchmark problem for comparison and validation of methodologies for
reliability assessment of passive safety system performance, including such issues as
systematic Failure Modes and Effects Analysis (FMEA), component failure rates, treatment
of dependencies in Fault Tree (FT) models, impact from internal and external hazards, etc.;
  • Select reliability assessment methodologies and perform trial applications, including
evaluation of the uncertainties, for a selected benchmark problem;
  • Compare the results and prepare recommendations for a common analysis-and-test based unified approach;
  • Draft suggestions for further elaboration of IAEA Safety Standards.

2.1 Summary of the activities

During the first meeting a number of activities have been identified to be developed
during the three years duration. These activities are listed hereafter:
  1) Elaboration of requirements to the method of reliability assessment of passive
     safety systems;
  2) Elaboration of a set of definitions for reliability assessment of passive safety
     systems and their treatment by PSA;
  3) Development, validation and verification of the methodologies:
     a. Validation of methodologies using tests;
     b. APSRA application to IRIS passive containment cooling system;
     c. Methods to minimize the number of calculations;
  4) Comparison of APSRA and RMPS and REPAS on a benchmark problem;
  5) Development of a framework for a databank of probability density functions for
     process parameters.

In this paper, for the sake of shortness an overview of the activities at points 4) and 5)
will be provided together with an overview of the methodologies for reliability analysis
of passive systems REPAS/RMPS and APSRA.

2.2 Overview of APSRA

In the APSRA methodology, the passive system reliability is evaluated from the
evaluation of the failure probability of the system to carryout the desired function.
Since applicability of the best estimate codes to passive systems are neither proven nor
understood enough, hence, APSRA relies more on experimental data for various aspects of
natural circulation such as steady state natural circulation, flow instabilities, CHF under
oscillatory condition, etc. APSRA compares the code predictions with the test data to generate
the uncertainties on the failure parameter prediction, which is later considered in the code for
prediction of failure conditions of the system.

The application of APSRA methodology foresees 5 steps hereafter shortly described.
Step I: Passive System for which reliability assessment is considered. In step I, the
passive system for which reliability will be evaluated is considered.
Step II: Identification of parameters affecting the operation. The performance
characteristic of the passive system is greatly influenced by some critical parameters. Some of
the critical parameters which influence the natural circulation flow rate in a boiling two-phase natural circulation system are:

- System pressure
- Heat addition rate to the coolant
- Water level in the steam drum
- Feed water temperature or core inlet subcooling
- Presence of non-condensable gases
- Flow resistances in the system.

Step III: Operational characteristics and failure criteria. In step III, APSRA requires the designer to have a clear understanding of the operational mechanism of the passive system and its failure, i.e., characteristics of the passive system. To judge its failure, the designer has to define its failure criteria. The characteristics of the system can be simulated even with simpler codes which can generate the passive system performance data qualitatively in a relatively short period. In this step, the purpose is just to understand the system operational behaviour but not to predict the system behaviour accurately. For this the designer has to use the parameters identified in Step II, which can influence on the performance of the system.

Step IV: Key parameters which may cause the failure. The studies in Step III and Step IV are complimentary to each other, in the sense that while the results of step III help in understanding the performance characteristics of the system due to variation of the critical parameters, step IV generates the results for those values of the critical parameters at which the system may fail for meeting any of the criteria given in Step II.

Step V: Generation of failure surface and validation with test data. Once the key parameters are identified in Step III (deviation of which can cause the failure of the system), the value of these parameters at which the system will fail, are calculated using a best estimate code. Hence there is another requirement for Step V, i.e., the results should be generated using a best estimate code such as RELAP5 in order to reduce the uncertainty in the prediction of the failure conditions. The results of Step IV generated using a simpler code is only useful in directing the inputs for Step V in order to derive the failure conditions rather quickly [10].

2.3 Overview of REPAS/RMPS

REPAS methodology has been developed in framework of cooperation between ENEA, University of Pisa, Polytechnic of Milan, and University of Rome.

The methodology was embedded in the Reliability Methods for Passive Safety (RMPS) methodology, developed within the framework of a project called RMPS functions, under the European 5th Framework program [6][7].

The methodology can be subdivided in the following main steps ([8][9]):

a) Characterization of design/operational status of the system (identification of relevant parameters connected with the TH phenomenon: design and critical parameters),

b) Definition of nominal values, range of variation and assigned probability distributions to design and critical parameters,

c) Deterministic (based on engineering judgment) and statistic (e.g., through Monte Carlo procedure) selection of system status,

d) Definition of failure criteria for the system performance (starting from the knowledge of the system mission and the identification of the accident scenario and allowing the definition of design targets for passive system); the failure criteria are established as single targets (e.g., the system shall 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 shall reject at least a mean value of thermal power all along the system actuation); in some cases, it can be better to define a global Failure Criterion (FC) of the complete system instead of a specific criterion concerning the passive system; for instance, the FC can be
based on the maximal clad temperature during a specified period; in this case, it is necessary to model the complete system and not only the passive system,
e) Detailed code modelling; once the system mission, accident scenario, and FC are established, a system model has to be developed by means of a best-estimate TH code (e.g., RELAP5),
f) Direct Monte Carlo simulation applied to TH code; it involves the propagation of the uncertain selected parameters through the considered TH code obtaining a model response (i.e., output variable) which allows, by means of statistic methods, to estimate the probability of failure of the passive function,
g) Sensitivity analysis,
h) Quantitative reliability evaluation.

2.4 Validation of the methodology for reliability analysis of passive systems

All of the methodologies are at a preliminary stage of development and no consensus on a common approach has been established so far among their proponents.

The validation of the methodology for reliability analysis of the passive safety systems is the main task of this CRP. For this purpose, a benchmark has been developed based on involving a real facility simulating a passive system based on the natural circulation phenomenon.

The experimental apparatus selected is a square shaped vertical natural circulation loop heated on the lower horizontal tube and cooled on the upper horizontal one (see Figure 1). The facility works at atmospheric pressure and is connected to an expansion tank placed in the upper part. The cooling at the heat sink is performed by a separate circuit where a mixture of water-glycol is kept in circulation at a fixed temperature imposed by the experimentalist. The facility is surrounded by an insulator that decreases the heat losses. About 20 thermocouples are placed in direct contact with the circulating fluid. This facility is sited at University of Genova (Italy) and it is managed by Prof. Misale and Prof. Devia.

This facility has been extensively used for studying the natural circulation in single phase [11][12][13].

Figure 1: L2 loop natural circulation facility

From a dataset available from previous experimental campaign, the loop shows a stable behaviour for a fixed value of the power at the heat source (lower horizontal tube) changing the temperature at the heat sink. The idea followed in the design of the benchmark is to fix the power at the source and to select a range of temperatures at the heat sink in the range where the behaviour of the natural circulation passes from unstable to stable regime. In this contest
the stable natural circulation has been considered when the direction of the fluid is the same; unstable in case the direction of the fluid oscillates during the experiments.

In these conditions we can evaluate the reliability of a real system to be compared with the results of the application of the methodologies for reliability analysis listed above.

The steps of the application are summarized in the flow diagram in Figure 2. The flow diagram is divided in two paths, one regarding the experimental activity and the other one the methodology application. At the end of each path we get the value of the reliability experimentally estimated and numerically simulated; the results of the two paths are compared.

At block (a), the preliminary analysis of the loop L2 has been performed based on already available results of previous experimental campaign in order to observe the loop behaviour.

Block (b): the parameters that can be modified in the loop facility L2 are identified and the related pdf are attributed by mean engineering judgment.

Block (c): based on the results of previous experimental campaign performed in the L2 loop that can be used for the purposes of the validation, additional tests can be planned specifically tailored on the purposes of the project.

Block (d): test execution on the facility L2.

Block (e): once the results of the experiments are available we have a number of tests in which the natural circulation is stable and the ones where is unstable. With this information it is possible to evaluate the reliability of the passive system.

On the other path of the flow diagram there are the steps of the methodology application for the evaluation of the reliability of the system numerically.

The numerical simulation start with the realization of the model for the codes adopted by each of the group involved in the CRP. In block (f) the model of the loop L2 is developed and qualified based on the available data.

Block (g): the pdf’s of the parameters implemented in the code are evaluated.

Block (h): the calculations are executed.

Block (i): the evaluation of the reliability of the passive system is performed by mean the methodologies REPAS/RMPS, APSRA.
Actually the experimental campaign has been concluded and the list of the executed experiment is reported in Table 1.

<table>
<thead>
<tr>
<th>No.</th>
<th>Power [kW] (Heater)</th>
<th>Temperature [°C] (Heat sink)</th>
<th>Number of runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.0</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>2.0</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>2.0</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>2.0</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>2.0</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>2.0</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>2.0</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>2.0</td>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>2.0</td>
<td>18</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 1: Test matrix

From the experiments has been observed that the transition between unstable/stable natural circulation has not a fixed temperature of the heat sink (once the power at the heat source is fixed) but there is an interval of temperature at the heat sink where the facility shows randomly stable/unstable behaviour. In the Figure 3 Figure 4 an example of this behaviour is shown. Increasing the temperature at the heat sink from the lowest one 4°C, the loop shows...
the tendency to stabilizes anyway from 10 °C to 11.4 ° (an higher temperature at the heat sink) the loop become unstable again.

Figure 3: Experimental results for temperature at heat sink of 10.0 °C

Figure 4: Experimental results for temperature at heat sink of 11.4 °C

Actually the experimental campaign is completed and the parameters have been selected together with their pdf’s. The qualification process of the L2 loop nodalizations developed by each group of the participants is on-going.

For the evaluation of the reliability of the loop L2 in the conditions realized in the experiments, the methodologies to the loop L2, has been agreed among the participants to execute 100 runs of code for each of the temperature of the heat sink as summarized in Table
It means 900 runs of code. This step is still on going and the complete results of the analysis will be complete at the end of November 2011.

This activity represents a first attempt for the validation of the methodology for reliability analysis of passive system. Different problems can be identified in the procedure because the system selected has very high probability of failure compared to the one adopted in the nuclear technology that have a low probability of failure. Anyway the relevance of this exercise is connected to the simplicity of the system and the limited number of parameters that have to be considered in the analysis.

2.5 Development of a framework for creating a databank to generate probability density functions for process parameters

During the application of the REPAS/RMPS methodologies and in general the PSA analysis requires the availability of best data of equipment and systems in the plant. In some cases very limited data may be available for evolutionary designs or new equipments, especially in the case of passive systems.

It has been recognized that difficulties arise in addressing the uncertainties related to the physical phenomena and characterizing the parameters relevant to the passive system performance evaluation, since the unavailability of a consistent operational and experimental data base. This lack of experimental evidence and validated data forces the analyst to resort to expert/engineering judgment to a large extent, thus making the results strongly dependent upon the expert elicitation process.

This prompts the need for the development of a framework for constructing a database to generate probability distributions for the parameters influencing the system behaviour.

The objective of the task is to develop a consistent framework aimed at creating probability distributions for the parameters relevant to the passive system performance evaluation.

In order to achieve this goal considerable experience and engineering judgement are also required to determine which existing data are most applicable to the new systems or which generic data bases or models provide the best information for the system design.

Eventually in case of absence of documented specific reliability data, documented expert judgement coming out from a well structured procedure could be used to envisage sound probability distributions for the parameters under interest.

In Table 2 there is the first attempt to create this databank with the aim to represent a reference for the designer and the analyst of passive safety system when he has to select a proper pdf for the interested parameters. The idea at the base of the databank creation is to generate with controlled experiments the pdf for the parameters that are employed in the analysis/design of a passive system. Because the number of parameters and the range of their variation can be very large and different, the problem arises to perform thousand of experiments in different conditions. This represents a huge and expensive task that cannot be completed in one project. The idea agreed during the CRP is to introduce in the databank data coming from previous experimental campaigns carried out by the CRP participants that are suitable for generate the pdf or from other sources as activities already performed and documented in journals, books etc.; this constitutes the starting point of a long process.
Table 2: Example of database for pdf of parameters relevant for passive systems

CONCLUSIONS

The paper summarizes the activities performed in the framework of the IAEA CRP131018: Development of Methodologies for the Assessment of Passive Safety System Performance, started in 2009 and in phase of conclusion at the end of 2011. Such methodologies require a preliminary validation process before they can be used in the normal PSA analysis for NPP components.

One of the main outcomes of the CRP is the elaboration of a benchmark for validation of two selected methodologies REPAS/RMPS and APSRA. A natural circulation loop facility has been selected for simulating the behavior of a passive system. A number of tests have been executed where in a part of them the natural circulation stable in the other one is unstable. The reliability obtained experimentally has to be compared with the one obtained by mean the application of the methodologies REPAS/RMPS and APRSA.

The activity described represents the first attempt of validation, due mainly to limited costs of the experiments and simplicity of the facility. More significant validation results can come from the analysis and reproduction of data coming from a passive system working a real NPP. This represents the natural evolution of this first validation attempt that is in course of discussion among the participant of the CRPI31018.

ACKNOWLEDGMENTS

The CRP participants gratefully acknowledge the contribution of Mr V. Kuznetsov, Ms S. Bilbao Y Leon, Mr A.S. Rao, Mr S. Michael Modro, Mr. Alexander Stanculescu for their contribution to the start of the activities and organization of this CRP.

REFERENCES


[5] F. D’Auria and G. Galassi, “Methodology for the evaluation of reliability of passive systems,” work performed in the frame of cooperation with DIMNP of Pisa University and ENEA (contract n. 9840 series 3A); DIMNP NT 420 (00) Rev. 01, October 2000.


