ANNEX 2: NEA NUCLEAR INNOVATION 2050

R&D COOPERATIVE PROGRAMME PROPOSAL

TITLE/SUBJECT: Passive Systems - by Jean Michel Evrard

1. Justification of the selection

After recent events, the accident of the Fukushima Daiichi nuclear power plant (2011) or the incident at the Forsmark power plant (2006), where reactor core cooling was (or could be) lost for a long period of time due to loss of electric power supply, attention is paid to passive safety systems not only for future reactor design but also for existing power plants.

Development of passive safety systems to nuclear power plants, which are already being in successful operation, is to be pursued as a step forward towards ultimate safety and therefore to (re)gain further acceptance of nuclear power in public, especially when it comes to plant lifetime extension.

On the other hand, internationally agreed documents about passive system safety demonstration have not been issued and no internationally-shared methods to consider passive-systems reliability assessment in existing probabilistic safety assessment (PSA).

It is therefore evident that there is a market need and a clear regulator request to further assess the performance of passive safety systems and their design tools. It is therefore indispensable for the nuclear sector to assess the technical feasibility of passive safety systems as well as their economic potential, compared to and in conjunction with active systems. The design of safe passive systems and their safety assessment, including an assessment of the codes used in the design process and an agreement on the methodology for assessment, are thus major objectives.

2. The issue to tackle and objectives to reach

The increased attention paid to passive systems raises some debate on passive systems application in nuclear safety and motivates their future development by the designers, research organizations and also TSOs involvement. Actually, specific questions are raised to assess the reliability of such systems (sensitivity to small changes of their environment, capacity to perform tests, qualification process…). In fact, the efforts conducted so far to deal with the passive safety systems, have raised an amount of open issues to be addressed in a consistent way, in order to endorse the proposed approaches and to add credit to the underlying models and the eventual reliability figures, resulting from their application and also consideration in the deterministic approach.

Owing to this, further development of knowledge must be seen in terms of diverse aspects like, for instance, involved phenomena, reliability, safety requirement specifications. The program will provide, primarily, the insights resulting from the analysis on the technical issues associated with assessing the reliability of passive systems (considering the physical phenomena involved in passive systems operating) in the context of nuclear safety and probabilistic safety analysis. Therefore the outline of a viable path towards the implementation of the research efforts with reference to the theoretical and experimental activities will be another goal of the program.

Passive systems and phenomena, namely but not only those where boiling and condensation take place in one loop:

- are prone to instabilities where instability depend upon initial and boundary conditions: i.e. one system stable if power is assigned may become unstable if power is supplied by another passive system (e.g. common situation of a passive system connected with Steam Generator of NPP);
- are affected by parameter uncertainties whose importance is negligible and are neglected when active systems are used: e.g. small inclination (construction tolerance) of horizontal pipes, small leakages of valves (acceptable when passive systems are not involved), presence of small fractions of non-condensable gases, un-characterized heat losses (irrelevant if pumps are used), pressure drops at geometric discontinuities (namely at low Re number under the conditions of flow reversal occurrences), initial distribution of temperature in vertical pipelines which determine the initial value of buoyancy forces.

Alongside, the development of a suitable methodology for the evaluation of passive systems requires the following steps:

- Deterministic approach and definition of safety design requirements for passive systems (single failure criteria (SFC), common cause failure (CCF), redundancy, diversity...) considering their role in the safety demonstration: activation, loading-up, performance of the safety function;
- Other requirements such as for qualification, for surveillance in operation (specific needs in terms of periodic-tests, maintenance, in-service inspection…);
- Specifics of passive system safety assessment considering internal and external hazards;
- Response of passive systems to design extension conditions (DEC) ;
- Methods for reliability assessment and for integration of passive systems within a PSA framework (including fault tree and event tree);
- Comparison between active and passive systems for each of the different aspects above, optimizing design considering both systems.

3. What is done/exist already, who is doing what, what are the means (resources and infrastructures)

Passive systems are more and more adopted as operational or safety system in both advanced NPPs (e.g. AP1000, APR1400, ESBWR) and SMRs (e.g., Nuscale, mPower, SMART).

The levels of development, or even the actual deployment of the concerned reactor designs (i.e. equipped with passive systems) for electricity production are very different, and the range of maturity of these extend from reactors already in operation to preliminary reactor designs which are not yet submitted for a formal safety review process.

A dozen different passive system types, having a few tens of reactor specific configurations, suitable to address safety functions in primary loop or in containment have been identified [1].

The types of advanced reactor passive safety systems for removing the decay heat from the core after a reactor scram are:

- Pre-pressurized core flooding tanks (accumulators),
- Elevated tank natural circulation loops (core make-up tanks),
- Gravity drain tanks,
- Passively cooled steam generator natural circulation,
- Passive residual heat removal heat exchangers,
- Passively cooled core isolation condensers,
- Sump natural circulation.

The types of advanced reactor passive safety systems for removing the heat from the containment and reducing pressure inside containment subsequent to a loss of coolant accident are:

- Containment pressure suppression pools,
- Containment passive heat removal/pressure suppression systems,
- Passive containment spray.

The thermal-hydraulic performance of the passive systems has been characterized by less than a dozen key phenomena at their time characterized through specific descriptions including a few tens of relevant thermal-hydraulic aspects.

Thermal-hydraulic phenomena and related parameter ranges that characterize the performance of passive systems do not differ in general from phenomena that characterize the performance of systems equipped with active components. This is specifically true for transient conditions occurring during safety relevant scenarios. In other words, one can say that friction pressure drops or heat transfer coefficients are affected by local velocity and void fraction and not by the driving force that establishes those conditions, e.g. gravity head or centrifugal pump. The same can be repeated for more complex phenomena like two phase critical flow or counter-current flow limiting.

The phenomena for passive systems were identified in the framework of the IAEA CRP on Natural Circulation Phenomena, Modeling and Reliability of Passive Safety Systems that Utilize Natural Circulation [2], considering the recently proposed passive systems by the industry:

- Behavior in large polls of liquid,
- Effects of non-condensable gases on condensation heat transfer,
- Condensation on containment structures,
- Behavior of containment emergency systems,
- Thermos-fluid dynamics and pressure drops in various geometrical configurations,
- Natural circulation,
- Steam liquid interaction,
- Gravity driven cooling and accumulator behavior,
- Liquid temperature stratification,
- Behavior of emergency heat exchangers and isolation condensers,
- Stratification and mixing of boron,
- Core make-up tank behavior.

There is the need to demonstrate the understanding of the key thermal-hydraulic phenomena that are selected for characterizing the performance of passive systems: this implies the identification of parameter ranges, the availability of proper experimental programs and the demonstration of suitable predictive capabilities for computational tools.

Comprehensive experimental and code development research activities have been conducted, also very intensely at an international level, in the past three to four decades in relation to the understanding of thermal-hydraulic phenomena and for establishing related code predictive capabilities for existing nuclear power reactors. In the same context, research activities also addressed some of the phenomena for passive systems. However, a systematic effort for evaluating the level of understanding of thermal-hydraulic phenomena for passive systems and connected code capabilities appears to be limited and in general lacking.

As regards reliability assessment methodologies for passive systems, specific developments have been conducted in Europe, in India and, to a less extent, in the US. An international workshop on passive system reliability was held by NEA (Working Group on Risk Assessment, WGRISK) in 2002, which concluded in particular that "*While work is being performed on methodologies and progress is being made, a lack of data exists mainly since very little or no operational experience is available. This is especially true in the area of thermal hydraulics and the result is a large amount of uncertainties*" [3].

The earliest significant effort to quantify the reliability of such systems is represented by a methodology known as REPAS (Reliability Evaluation of Passive Systems) [3], which has been developed in late 1990s, cooperatively by ENEA, the University of Pisa, the Polytechnic of Milan and the University of Rome, that was later incorporated in the EU (European Union) RMPS (Reliability Methods for Passive Systems) project [4]. The RMPS methodology was developed to address the following problems: (1) Identification and quantification of the sources of uncertainties and determination of the important variables, (2) propagation of the uncertainties through thermal–hydraulic (T–H) models and assessment of passive system unreliability and (3) introduction of passive system unreliability in accident sequence analyses. In this approach, the passive system is modeled by a qualified T–H code (e.g. CATHARE, RELAP) and the reliability evaluation is based on results of code runs, whose inputs are sampled by Monte-Carlo (M-C) simulation.

A different approach is followed in the APSRA (Assessment of Passive System Reliability) methodology developed by BARC (Bhabha Atomic Research Centre, India) [5]. In this approach, a failure surface is generated by considering the deviation of all those critical 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 foresee to use in-house experimental data from integral facilities as well as separate.

In the US, the MIT research on the reliability of passive safety systems has focused on a different set of reactor technologies. Their research has examined thermal–hydraulic uncertainties in passive cooling systems for Generation IV gas-cooled reactors [6]. Instead of post-design probabilistic risk analysis for regulatory purposes, the MIT research seeks to leverage the capabilities of probabilistic risk assessment (PRA) to improve the design of the reactor systems early in their development life cycle.

In 2012, IAEA launched a Coordinated Research Project (I31018) entitled ''Development of Methodologies for the Assessment of Passive Safety System Performance in Advanced Reactors'' [7]. Argentina, France, India, Italy and the Russian Federation participated in this project, completed in 2013. The principal conclusion of this CRP was: '' *There is a clear need to obtain more data, especially* *related to thermal hydraulics. This necessitates additional development, testing and research. It is essential that passive and evolutionary components, Common Cause Failures (CCF) of high redundancy systems and intersystem CCF of advanced reactors are adequately addressed. The technical challenges for such reactors also include the potential need to address very different systems and phenomenology, the potential unavailability of important reliability and experimental data, the potential unavailability of knowledge on new key phenomena, and the potential unavailability of accident analysis models.*''

In [8], L. Burgazzi considers the assessment of the reliability of passive systems in the frame of plant safety and risk studies as still an open issue: "*The complexity stems from a variety of open points coming out from the efforts conducted so far to address the topic and concern, for instance, the amount of uncertainties affecting the system performance evaluation, including the uncertainties related to the thermal–hydraulic (T–H) codes, as well as the integration within an accident sequence in combination with active systems and human actions. These concerns should be addressed and conveniently worked out, since it is the major goal of the international community to strive to harmonize the different proposed approaches and to reach a common consensus, in order to add credit to the underlying models and the eventual out coming reliability figures.*"

4. What can be done to improve/accelerate, ia through cooperation

The objective followed is not to consider the development or the validation of some passive system designs, but to develop commonly-recognized methods and produce necessary data to assess the reliability of such systems in safety demonstrations, which is a key step in their generalized used in nuclear reactors.

From the previous discussion, we can infer that the needs for knowledge/methodology improvement are the following (and corresponding actions within NEA):

- Based on the identification on thermal-hydraulic phenomena involved in the various passive system types considered in new designs or in a back-fitting of existing plants perspective, determine how to achieve enough precise and robust modelling of such phenomena, in normal and accidental conditions, including their response to external events (WGAMA).
- Based on the methodologies proposed to assess the reliability of passive systems, propose an internationally-shared methodology including uncertainty assessment (WGRISK).
- Identify experimental data needed for supporting the qualification of modelling and reliability assessment, identify experimental facilities which could provide these data and propose a joint research project.

It is to be outlined that the production of experimental data is a key objective and a necessary input for the further development of modelling and reliability assessment methodology and that these three aspects should be dealt with in close interaction.

5. Plan of Actions and necessary means (resources and infrastructures)

To be further developed.

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