Regulatory Guidance on the Reliability and Performance of Nuclear Passive Safety Systems

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Abstract

The reliability and performance of passive safety systems (PSSs) has become an important subject and area under discussion, for their extensive use in advanced nuclear power plants (NPPs). These PSSs in their designs rely on natural forces to perform their accident prevention and mitigation functions once actuated and started. However, the weak driving forces of many of such PSS based on natural circulation and small pressure differences pose significant challenges to the design and safety demonstration of PSS for a broad range of accident conditions. In addition, nuclear regulators worldwide are facing important challenges in the licensing of the PSSs in an advanced reactor designs. The number of studies that have discussed the regulatory perspective on the reliability and performance of PSSs is limited and has not provide clear guidance due to their complexity. The objective of this paper was first to review the previous studies related to the reliability and performance assessment of the PSSs, to review current regulatory guides and standards on the PSSs either in the requirements of the IAEA or national regulatory bodies, and to propose new regulatory approach and guidance concerning the performance and reliability of the PSSs in NPPs. In this paper, survey of existing systems and activities, methods for simulation and reliability assessment of the PSSs, considerations for safety and design of the PSSs are covered. This paper also identifies ongoing issues and concerns to the reliability and performance of the PSSs and suggest few areas in order to properly assess them.

Keywords: passive safety system, performance, reliability

1. Introduction

In recent years, advanced technologies of NPP are making more extensive use of passive safety features for a variety of purposes, for instance for core cooling during transients, design basis accident, and severe accidents or for containment cooling, with the claim that PSSs are highly reliable and reduce the cost associated with the installation and maintenance of systems requiring multiple trains of equipment requiring expensive components such as: pumps, motors and other equipment as well as redundant safety class power supplies. However, the weak driving forces of many of such PSSs based for instance on natural circulation and small pressure differences pose significant challenges to the design and safety demonstration of PSS for a broad range of accident conditions and also additional loads that can be posed by internal or external hazards.

Nuclear regulatory bodies worldwide are facing also important challenges in the licensing of the new passive and innovative reactor designs. For demonstrating the reliability and performance of PSSs or safety features also addressing the independence of the different levels of defence in depth, the requirements for design, methods and computational tools for analyses of the physical phenomena as well as experimental tests for validation are of capital importance.

Therefore, there is an urgent need to assess the reliability and performance of these systems in the advanced technologies of NPPs. There have been several efforts by IAEA and academic organizations to understand the performance and reliability of the PSSs, however, there are still several issues to clarify them for the review of the PSSs.

This research focuses on reviewing the previous studies related to the passive safety system reliability and performance assessment, reviewing current regulatory guides and standards on the PSSs either in the requirements of the IAEA or national regulatory bodies, and suggest a regulatory guidance concerning the performance and reliability of the PSSs in NPPs.

2. Performance and Reliability of the Passive Safety System

Concerning the performance of safety function, for systems relying on low driving forces the range of conditions necessary to perform the safety function could be narrow. Thus, Demonstration that a passive system can ensure a safety function with a high level of reliability should recognize and, when relevant, address the following [1]:

a) Comprehensive knowledge and understanding of phenomena and parameters that could influence the performance or failure of a passive system should be established considering the driving forces involved.

b) The impact of environmental conditions on system performance needs to be considered and a passive system could be particularly sensitive to these environmental conditions.

c) The application of concept of margins, especially to ensure distance to cliff-edge effects, could be more demanding considering, notably, the uncertainties in the performance of passive systems.

d) It is necessary to consider that passive systems performance may show a dynamic behavior.

3. Regulatory Guides and Standards on Passive Safety System

By comparing the various methodologies of relilabity and performance assessment of PSSs, the Advanced Light Water Reactor (ALWR) Utility Requirements Document (URD) in US, specifies standards concerning the design and performance of active systems and equipment that perform non-safety-related, defense-in-depth functions. These standards include radiation shielding, redundancy, availability of non-safety-related electric power, and protection against more probable hazards. However, the ALWR URD did not include specific quantitative standards for the reliability of PSSs. Appropriate levels of reliability and availability for these systems are established with the Reliability Assurance Program (RAP) and Regulatory Treatment of Non-Safety Systems (RTNSS) process. This process used by the designer to specify and establish the Relaibilty / Availibity (R/A) missions for the risk significant Systems, Structures and Components SSCs. and then to impose design requirements commensurate with the risk-significance of those elements involved.

However, If active systems are determined to be risk-significant, the NRC reviews the R/A missions to determine if they are adequate and whether the RAP and administrative controls on availability, or simple TSs and Limiting Conditions for Operation can provide reasonable assurance that the missions can be met during operation. [2,3]

While, in Korea, a regulatory review was performed during the design review of the passive auxiliary feed-water system of APR+ and the passive residual heat removal system of SMART [4]. As a general requirement, it is required that the PSS should perform the safety function which is required to the active safety system, and there should not be issues which could influence to the nuclear safety due to the inherent design characteristics of the PSS [5].

As indicated at the IRSN, France in the World Nuclear News in Jan. 2016 [6], further research is required to properly assess the performance and reliability of the PSS and should focus on understanding the physical phenomena influencing their operation, simulation capabilities for such phenomena, and testing for validation of simulation software.

4. Suggestion for Future Study on the Reliability and Performance of the PSSs

The PSSs may contribute to improving the safety of NPP, provided related safety targets are demonstrated by methods, approaches and data (e.g. experimental database) available to industry and to regulators.

It is suggested that regulatory guidance should consider the issues and concerns based on recent studies and research. Selected results of investigations which brought to the key conclusion are synthesized as follows [7]:

- One passive safety system (e.g. working in natural circulation) is typically found to satisfactorily accomplish the target mission when one or a few operational scenarios are investigated; each operational scenario necessarily implies transient conditions and several hours duration.
- When a large spectrum of scenarios, in the order of different thousands, is analyzed, failures are found in relation to target mission: this has been demonstrated by the application of REPAS and RMPS methodologies at the beginning of the year of 20’. The failure probability of the passive system was associated with the integral over the fault sequence probabilities for which the PSS does not meet its performance requirements and an acceptance criterion is not met; a difficulty here consists in determining the probability for the occurrence of each failed-scenario.
- It is not practically possible to perform in test facilities the needed large number (e.g. different thousands) of experiments; performing an equivalent number of numerical simulations, as a surrogate of the experiments, is possible for complex (passive) nuclear systems (e.g. AP-1000), but can be extremely expensive and requires a full qualification of the simulation tools.
- It is important to point out the key role that thermal-hydraulic system codes have in evaluating the

reliability of passive systems: calculated results are often questionable also for motivations outside the structure and the capabilities of those codes.

5. Conclusion

Reliability assessment of the PSS is still one of the important issues. Several reliability methodologies such as REPAS, RMPS and APSRA have been applied to the reliability assessments. However, some issues are remained unresolved due to lack of understanding of the treatment of dynamic failure characteristics of components of the PSS, the treatment of dynamic variation of independence process parameters such as ambient temperature and the functional failure criteria of the PSS.

Dynamic reliability methodologies should be integrated in the PSS reliability analysis to have a true estimate of system failure probability. The methodology should estimate the physical variation of the parameters and the frequency of the accident sequences when the dynamic effects are considered.

This study has examined the interest of using passive safety systems (PSSs) in advanced nuclear reactors against consequences following accident conditions. Besides, evaluating the performance and reliability of PSSs under a regulatory approach to define acceptance criteria regarding using PSSs in nuclear power plants.

The ongoing issues and areas for further studly are as follows:

1) Performance assessment:
   - The physical phenomena related to the operation of PSSs, and how to simulate these phenomena in the thermal-hydraulic (T/H) codes should be understood presisely.
   - As the performance is very depending on conditions of operation, assessing the performance of PSSs requires a very good understanding of the physical phenomena underlying their operation, as well as the necessary simulation capabilities for such phenomena
   - Capacity of the passive system should be validated and verified to ensure the safety function with the expected performance.
2) Reliability assessment:
   - Because of the specific characteristic of PSSs that utilize driving force to activate and operate, assessing their failure probabilities related to T/H mechanisms used by such systems.
   - Though on the results of previous research regarding reliability assessment of PSSs, the critical aspects of qualitative analysis that is identified and included of uncertainties, the dependencies among the T/H parameters, and the incorporation of reliability models in PSA.
   - Specific development approaches appear to be necessary in order to properly evaluate the reliability of passive safety systems, with particular emphasis on assessing the failure probabilities of thermal-hydraulic mechanisms used by these systems.

Recently, the generic data of passive safety systems has not been accomplished, and the trend of enhancing using PSSs in new reactor designs that has been considered to bring and maintain a safe shutdown state for reactor without human intervention.

Further research can be conducted to accomplish data library of PSSs by using the other approach to assess properly their performance and reliability in new reactor designs. Based on these generic data, the extensive use of PSSs that is developed for next generation nuclear reactor designs to prevent accident consequences.

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