A Regulatory Perspective on the Performance and Reliability of Nuclear Passive Safety Systems

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1. Introduction

As part of the IAEA's overall effort to improve the economics and safety of future water-cooled reactors, their new designs "focus on the use of passive safety systems(PSS) to help meet the safety and economic goals of a new generation of nuclear power plants" [1]. Therefore, advanced nuclear power plants (NPPs) increasingly use passive systems, aimed at both significant simplification and enhanced reliable, as regards in particular human error and failure of active components in particular.

Passive safety systems have been proven to enhance the safety of NPPs. When an accident such as station blackout occurs, these systems can perform the following functions: the decay heat removal, passive safety injection, containment cooling, and the retention of radioactive materials [2]. Following the IAEA definitions, using passive safety systems reduces reliance on active components to achieve proper actuation and not requiring operator intervention in accident conditions. However, their operation bases on physical phenomena that generally involve driving forces, as natural convection, pressure, and conduction. In fact, such phenomena may be sensitive, and there are deviations of the natural forces or physical principles. That leads to the deviations in boundary conditions of the critical process or geometric parameters, which activate and operate the system to perform accident prevention and mitigation functions. The main difficulties in evaluation of functional failure of passive systems arise because of (a) lack of plant operational experience; (b) scarcity of adequate experimental data from integral test facilities or from separate effect tests in order to understand the performance characteristics of these passive systems, not only at normal operation but also during accidents and transients; (c) lack of accepted definitions of failure modes for these systems; and (d) difficulty in modeling certain physical behavior of these systems.

Furthermore, the current regulatory guides or standards for the performance and reliability of the PSSs are not adequately provided in detail during licensing of new generation of reactor designs. It is anticipated that the regulatory standards will continue to experience a shift towards best-estimate methodologies and risk-based metrics, particularly with regard to the analysis of the performance and reliability of the PSS.

This paper is organized as follows: review previous studies on passive safety system reliability analysis to figure out the critical issues that need to be resolved within a regulatory frame work; review current regulatory guides & standards on the PSS; suggestions for future regulatory approach and guidance concerning the performance and reliability of the PSSs in NPPs.

2. Methodology

In order to quantify the reliability of PSSs, many assessment methods have been used and applied to advanced reactor designs. Methods such as reliability evaluation of passive safety system (REPAS), reliability methods for passive safety functions (RMPS), and analysis of passive systems reliability (APSRA) have each been developed in the past decades [3].

In REPAS, the failure probability of passive systems was evaluated by propagating the epistemic uncertainties of important physical and geometric parameters, which affect system performance the most. However, in order to assess the impact of uncertainties on the predicted performance of passive systems, a large number of calculations with best estimate codes were needed.

In RMPS, the treatment of input parameter variations is done by using the probability density function and the performance of a passive system is then evaluated using best estimate codes such as RELAP5 or CATHARE. Using results of these code runs, the probability of passive system failure is estimated. However, implementing the RMPS procedure for reliability assessment of passive systems and for RMPS integration with plant-specific PSA has certain shortcomings, such as not account for the interaction between (a) hardware/component failure and (b) functional failure of passive systems.

Another methodology, APSRA has following features in common with RMPS: used best estimate codes to find the thermal-hydraulic (T-H) performance of the passive systems and the influence of sensitive parameters: defined T-H failure criteria of the system, used probabilistic and deterministic tools to assess the reliability of the system. In addition, APSRA predicts failure surface and evaluates reliability of the passive systems using fault tree analysis. While these methodologies have certain features in common, they differ in the consideration of certain issues; for example, treatment of model uncertainties, deviation of geometric and process parameters from their nominal values.

3. Open issues

By comparing the various assessment methodologies, the studies of L. Burgazzi [4] has demonstrated the open issues related to using PSSs in nuclear power plants, the following open questions are highlighted and need to be considered within a regulatory framework: (a) performance assessment: to conduct this assessment need to understand precisely the physical phenomena related to the operation of PSSs, and how to simulate these phenomena in the (T-H) codes, (b) reliability assessment: because of the specific characteristics of PSSs that utilize driving force to activate and operate, assessing failure probabilities related to T-H mechanisms used by such systems. According to the results of previous research regarding reliability assessment of PSSs, the critical aspects of qualitative analysis that is identified and included in uncertainties, the dependencies among the T-H parameters, and the incorporation of reliability models in PSA.

In another study on passive system reliability done in India, there are three critical issues pertaining to passive systems performance and reliability have been identified [3]. The first issue is applicability of best estimate codes and model uncertainty. The best estimate codes based on phenomenological simulations of natural convection passive systems could have a significant amount of uncertainties, which must be incorporated in an appropriate manner in the performance and reliability analysis of such systems. The second issue is the treatment of dynamic failure characteristics of components of passive systems. The REPAS, RMPS, and APSRA methodologies do not consider dynamic failures of components or process, as which may have a strong influence on the failure of passive systems. The influence of dynamic failure characteristics of components on system failure probability is presented with the help of a dynamic reliability methodology based on the Monte Carlo simulation. It is thus suggested that dynamic reliability methodologies must be integrated in passive systems reliability analysis to have a true estimate of system failure probability, and hence the reliability. The third issue is the treatment of independent process parameter variations in to passive system reliability analysis. Certain process parameters such as atmospheric temperature, can vary with time. The performance of some passive safety systems depends on this parameter. However, the present methodologies do not consider this dynamic variation from the nominal values and hence open a subject for discussion.

Recent method for the assessment of passive system reliability that is discrete dynamic event trees (DDETs) was presented in the studies of Argonne National Laboratory, U.S [5]. In order to calculate failures in passive system, there is necessary an explicit analysis for event trees, so time-dependent need take into account in reliability methods. To account for this, the utilization of DDETs, which explicitly treat time, allows for a mechanistic and consistent treatment of failures and the phenomenology driving passive systems.

Construction of DDETs is accomplished by coupling a system model with a set of branching rules that describe behavior of the system probabilistically. The analysis begins with a single initiating event and the simulation proceeds in time until a user-defined branching criterion (typically a state variable) is achieved. At this point, the simulation is halted, and the scenario bifurcates to generate two parallel scenarios, where one scenario contains the occurrence of the branching event, and the other does not. The simulations proceed as before, until the next branching criterion is reached, where branching will then occur again. Though on this studies, there are following advantages of DDETs for treatment of passive system failure: incorporate non-binary branches (e.g. degraded operating state); treat failure as a true function of boundary condition using system-level codes; consider wide range of uncertainties affecting passive system performance as shown in Fig.1.

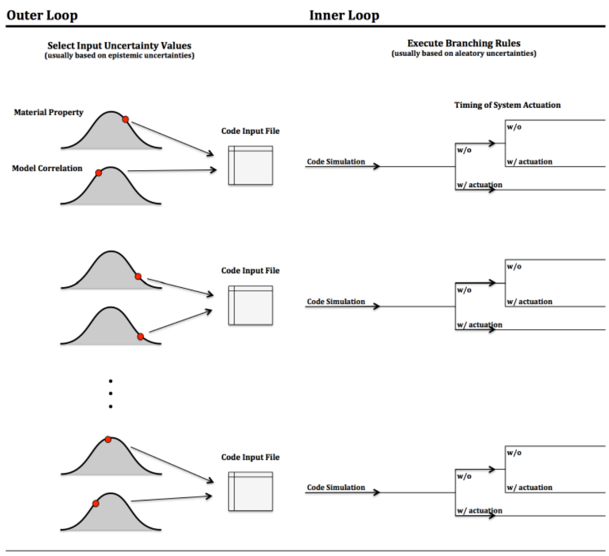

Fig.1. Strategy for treatment of uncertainties in DDET analysis [6]

Other effort to consider a dynamic reliability of the PSS is suggested by APSRA+ [7]. Important features of APSRA+ are the following. First, it provides an integrated dynamic reliability method for the consistent treatment of dynamic failure characteristics such as multistate failure, fault increment, and time-dependent failure rate of components of passive systems. Second, this methodology overcomes the issue of process parameter treatment by just the probability density function or by root cause analysis, by segregating the parameters into dependent and independent process parameters and then giving a proper treatment to each of them separately. Third, the methodology treats the model uncertainties and independent process parameter variations in a consistent manner.

4. Regulatory Guides and Standards on Passive Safety System

In US, the Advanced Light Water Reactor (ALWR) Utility Requirements Document (URD) for passive plants [8] issued March 1999 by the Electric Power Research Institute, 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 to permit access after an accident, redundancy for the more probable single active failures, availability of non-safety-related electric power, and protection against more probable hazards. The standards also address realistic safety margin analysis and testing to demonstrate the systems' capabilities to satisfy their non-safety-related, defense-in-depth functions. However, the ALWR URD does not include specific quantitative standards for the reliability of these systems. 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. The scope, criteria, and process used to determine RTNSS for the passive plant designs are established in SECY-94-084 [9] and SECY-95-132 [10]. They describe the scope, criteria, and process used to determine RTNSS in the passive plant designs.

The following five key elements make up the process:

1) The ALWR URD describes the process the designer should use to specify the reliability/availability (R/A) missions of risk-significant Systems, Structures and Components (SSCs) needed to meet regulatory requirements and to allow comparisons of these missions to USNRC safety goals. An R/A mission is the set of requirements related to the performance, reliability, and availability of an SSC function that adequately ensures the accomplishment of its task, as defined by the focused PSA or deterministic analysis.

2) The designer applies the process to the design to establish R/A missions for the risk significant SSCs.

3) 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 (SRP 17.4) and administrative controls on availability, or simple TSs and limiting conditions for operation (LCOs) can provide reasonable assurance that the missions can be met during operation.

4) If active systems are relied on to meet the R/A missions, the designer imposes design requirements commensurate with the risk-significance of those elements involved.

5) The design certification rule does not explicitly state the R/A missions for risk-significant SSCs. Instead, the rule includes deterministic requirements for both safety-related and non-safety-related design features.

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. 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. The US review process and standards are in principle applied to the review and more detailed analysis were additionally requested to conform the performance of the PSS. Detailed regulatory guides and experiences are described in the Refs. [11, 12].

As indicated at the IRSN, France in the World Nuclear News in Jan. 2016, 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.

5. Concluding Remarks

Reliability assessment of the PSS is still one of the important issues. Several reliability methodologies such as REPAS, RMPS and ASPRA 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.

In the present study, it is recommended that recent approaches such as APSRA+ or DDET could be to resolve the open issues above and further to be utilized in the regulatory review of the PSS.

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