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Reliability assessment and data processing techniques of the squib valve in pressurized water NPPs

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ABSTRACT

As for the passive PWR NPP, the SV plays a crucial role in nuclear accident mitigation. Since the reliability test of SV is destructive, it is too pricy to perform large sampling of repetitive tests to acquire data. Instead, this paper introduces an economical methodology with small sample tests which is suitable for the SV reliability assessment. Based on the FMEA results, the components of cartridge and mechanical parts are identified as principal contributors and analyzed meticulously. Data processing techniques within the framework of Bayesian inference are developed so as to achieve data format consistency in data aggregation and perform uncertainty analysis by Monte Carlo approach. The main findings of this paper are the practical methodology of assessing the SV reliability and convincing results which solve an issue in the passive PWR NPP safety review.

1. Introduction

The squib valve (SV) is a critical component in the engineered safety systems of the passive nuclear power plants such as AP1000, CAP1000 and CAP1400 nuclear power plants (NPPs). Whether the squib valves perform their safety functions successfully or not is crucial to the safety of the NPPs. From the results of failure modes and effects analysis (FMEA), there are several failure modes of the squib valve, such as failure to open, spurious actuation, and failure to maintain boundary integrity after actuation. Behind these failure modes are dozens of specific causes. Among these failure modes, the failure to open is identified to be the major one. The probability of spurious actuation can be reduced to a negligible level by improving the design of instrument and control systems. The accident of spurious actuation can also be mitigated by preventive design, e.g. check valves on upstream locations, and bounded by initiating events addressed in the probabilistic risk assessment (PRA, or PSA). The failure to maintain boundary integrity after actuation is unique for the valve with two shear caps and minor in contribution to the plant safety. Among all the failure modes identified, the mechanisms behind failure to open are relatively more complicated and difficult to control than the others. In this paper, the reliability assessment focuses on the failure to open on demand and, the discussion is dedicated to this failure mode.

1.1. Background and advances

Generally, there are two ways to assess the reliability of the squib valve. The first way is calculating the failure times out of demands as probability through cumulative data from either operating NPPs, or overall tests of assembled SV, or the both. However, this empirical accumulation is only counting the SV failures upon demands for statistical quantification, without focusing on the specific mechanism and reliability of individual components in a SV. The second way to the squib valve reliability assessment is to analyze the component reliability of squib valve, piece by piece, before reliability parameters of each component are aggregated through the logical relationship among those components.

In the industrial reliability generic database issued by Nuclear Regulatory Commission (NRC) (Eide, 2007), the probability of squib valve failure to open is 1.0E − 03 on average or the reliability is 0.999. This value is calculated based on the 0 failure out of 468 demand records of the squib valve collected from boiling water reactor (BWR) NPPs. Jeffery's noninformative prior is employed in Bayesian inference as there is not a failure case recorded. In contrast to BWR, there are only 87 reliability test records of the prototypes of squib valve in pressurized water reactor (PWR) NPPs all over the world. These tests are for the SV in passive NPPs in China. No failure has been reported among the 87 prototype tests of PWR either. In the safety review of the passive PWR, it is controversial whether the BWR squib valves reliability data can reflect or represent the reliability of PWR counterparts, regarding the differences in design, manufactures, operation conditions, and maintenance between BWR and PWR squib valves. If sufficient data of particular squib valves for PWR are available, quantitative assessment on their reliability would be more credible. However, the squib valves

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Nomenclature

ADS	Automatic Depressurization System
BWR	boiling water reactor
Beta(α,β)	Beta distribution with parameters α and β
CCF	common cause failure
C_m^n	the number of combinations of m things taken n at a time
EV	explosive valve (the same as squib valve)
f	the number of failure times within n trials of a 0–1 test
FMEA	failure modes and effects analysis
IRWST	In-Containment Refueling Water Storage Tank
IST	in-service testing
MGL	Multiple Greek Letters
n	the number of trials of a 0–1 test
NPP(s)	nuclear power plant(s)
NRC	Nuclear Regulatory Commission
pd	probability density
PDF	probability density function
P_i	percentile i
PRA	probabilistic risk assessment
PSA	probabilistic safety assessment
PV_i	percentile value i
PWR	pressurized water reactor
R_L	lower confidence limit of reliability
R_1	reliability of one igniter
R_{1L}	lower confidence limit of one ignition reliability
R_2	reliability of detonation propagation
R_{2L}	lower confidence limit of detonation propagation reliability
R_3	reliability of shear cap severance
R_{3L}	lower confidence limit of shear cap severance reliability
R'	reliability of the squib valve with one shear cap
R'_L	the lower confidence limit of the reliability of the squib valve with one shear cap
R'_{mean}	the mean value of the reliability of the squib valve with one shear cap
R''	reliability of the squib valve with two shear caps
R''_L	the lower confidence limit of the reliability of the squib valve with two shear caps
R''_{mean}	the mean value of the reliability of the squib valve with two shear caps
s	the number of success times within n trials of a 0–1 test
SNERDI	Shanghai Nuclear Engineering Research & Design Institute
SV	squib valve
X_L	piston impulse velocity
X_S	velocity criticality on demand for cap severance
Z	stress margin in the stress-strength model
α	the shape parameter of a Beta distribution
β	the scale parameter of a Beta distribution
γ	confidence level
μ	mean value of a Normal distribution
μ_L	mean value of piston impulse velocity L
μ_S	mean value of velocity criticality on demand for cap severance S
μ_Z	mean value of the stress margin Z
σ	standard deviation of a Normal distribution
σ_L	standard deviation of piston impulse velocity L
σ_S	standard deviation of velocity criticality on demand for cap severance S
σ_Z	standard deviation of the stress margin Z
$\Gamma(\cdot)$	Gamma function
$\Phi(\cdot)$	cumulative distribution function of standard Normal distribution

remain closed when the NPPs normally operates, actuated only in rare accident cases. On the other hand, the reliability test of the squib valve is destructive, with most of the squib valve parts damaged and hardly reused after test. If the reliability of the valve is assessed via attributes sampling test, with respect to the binomial distribution property, at least 2994 trials are needed to reach the accuracy of reliability value 0.999. Therefore, a large number of attributes sampling tests to obtain the quantitative assessment are not feasible because of the enormous cost. This is the nature of the squib valve as well as most pyrotechnical devices. Only a few test data of prototypes or models of the squib valve are available. These data can be amalgamated with the generic data by Bayesian updating method to obtain the reliability assessment results, which is mentioned as a comparison in Section 7 of this paper.

In the review of AP1000 NPP in the United State, the NRC once required the manufacturer of SV to submit the reliability assessment results of their SV. Then the manufacture performed the sensibility test of the igniter by the Bruceton method, and the output test of the cartridge with less charging loaded. However, their results are inadequate in the precision of the pyrotechnic part and lack of assessment of the mechanical part, so that they lend little support to the SV reliability in the AP1000 NPPs in China.

1.2. Objective and scope of the studies

Between the two methods of reliability assessment mentioned in Section 1.1, the second method is much more feasible than the first one. Thus this paper focuses on the second one. As for the pyrotechnic reliability assessment, an eclectic method consisting of attributes sampling and variables sampling tests and quantitative analysis is introduced, based on the results of failure mode and effect analysis. The reliability analysis of the mechanical part is performed on the stress-strength interference model, drawing conclusions of material tensile test and piston velocity measurement. This methodology is valuable to the reliability assessment and assurance of the squib valve. Fig. 1 shows the squib valve on the testing facility of a supplier in China.

Mathematical and statistical knowledge are utilized to develop data processing techniques throughout the entire process of reliability tests and quantification. These techniques cover the probability density curve fitting, data format transformation, and uncertainty analysis by Monte Carlo method, etc.

2. Functions and mechanisms of squib valve components

In the design of AP1000, CAP1000 and CAP1400 NPPs, there are three locations in the engineered safety systems that are equipped with squib valves, where all the squib valves are normally closed. The three locations are Automatic Depressurization System (ADS) stage 4 pipes, In-Containment Refueling Water Storage Tank (IRWST) injection lines, and the Containment Recirculation lines (Hashim et al., 2014; Quan et al., 2016). In accident scenarios, these squib valves open when receiving signals of actuation.

- For ADS stage 4 pipes, when the squib valves are actuated, reactor coolant in the primary loop is discharged into the environment in the containment through the open squib valves.
- For the IRWST injection lines, when the system is actuated, the normally closed squib valves on the IRWST injection lines open, allowing the water in the IRWST to flow to the reactor core through the direct vessel injection lines.
- For the containment sump recirculation lines, when the system is actuated, the normally closed squib valves on the Recirculation lines open, allowing the water in the containment sump to provide