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Reliability analysis of ASME Class 2 high energy pipings

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ABSTRACT

This paper presents the basic ideas for development and application of reliability based in-service inspections of ASME Class 2 and 3 pipings. This group includes all steam pipings and feedwater lines inside and outside hermetic zone. Based on the ASME Code, Section III, Articles NC/ND 3653 the reliability indices for protection of pipings against plastic collapse and postulated pipe rupture are derived. The general flow chart of the main steps involved in the optimised inspection planning is developed. The target values of reliability indices are based on the International Atomic Energy Agency defense in depth philosophy.

1) INTRODUCTION

When early commercial nuclear reactors were designed a limited experience with piping materials for nuclear power plants (NPPs) existed. In all countries the standards for power piping have been applied, for example B 31.1 code and the main purpose was to protect the pipework against plastic collapse. Later the special nuclear standards as ASME Code Section III came in force and for the purposes of Preliminary and Final Safety Analysis Reports PSAR and FSAR the special pipe rupture requirements were formulated as well as the protection measures like physical separation of safety related pipings, installation of pipe whip restraints and barriers against jet impingement forces. Note that all this methodologies are deterministic and are based on the allowable stress format.
Starting from the well-known WASH 1400 report, the PRA studies significantly influenced the nuclear safety philosophy. Although the licensing of the new and older NPPs is deterministic, the results of PRAs are taken into account as an effective tool for decision making of nuclear authorities as well as for planing of preventive or corrective maintenance. Unfortunately, the limitation of current PRA is the modelling of pipework systems and their components. In view of the world wide industrial operating experience, the passive equipment can (and often does) induced significant accident scenario as high energy pipe break (HELB) with related consequences.

From this reasons, researches have worked on various aspects of pipework reliability over past two decades but no current data source based on the worldwide experience with piping and their components reliability yet exists. The aim of this paper is to contribute to this problem in the field of reliability analyses of ASME Class 2 and 3 pipings as the possible approach to at present devéloped "reliability based in-service inspections".

2) DERIVATION OF RELIABILITY INDICES $(ri)_1$ AND $(ri)_2$

For the design of ASME Class 2 and 3 high energy pipings there exist three mandatory requirements:

- protection against plastic collapse
- protection against postulated pipe whip effects and jet impingement forces
- avoidance physical separation.

Due to historical reasons, the secondary pipings of the NPPs with WWER type reactors do not fulfil second and third requirement and the additionally analyses and protective measures are now performed.

The in-service inspections must be concentrated on the significant degradation effects, i.e. on the wall thinning due to corrosion-erosion.

The deterministic methodology for protection against plastic collapse is based on the well known ASME Code, Section III, Articles NC/ND 3653 equations (9), i.e.

$$\sigma_{red} = (\sigma)_2 + (\sigma_D)_2 \leq 1.8\ [\sigma] \tag{1}$$

where

$(\sigma)_2$ membrane and bending stresses due to inner pressure, dead weight and other sustained loadings

$(\sigma_D)_2$ membrane and bending stresses due to occasional loadings such as steam/water hammer events or earthquake

$[\sigma]$ allowable stress at working temperature which represents the minimum value from $\left(\frac{R_m}{2.6};\ \frac{R_{p0.2}}{1.5}\right)$

The deterministic methodology of prediction of rupture locations is based on the sum of ASME Code, Section III, Articles NC/ND 3653 equations (9) and (10), i.e.

$$(\sigma)_2 + (\sigma_D)_2 + i(\sigma_T)_2 \leq 0.8(1.8[\sigma] + \sigma_A) = R_1 \tag{2}$$

in the containment penetration area or

$$(\sigma)_2 + (\sigma_D)_2 + i(\sigma_T)_2 \leq 0.8(1.2[\sigma] + \sigma_A) = R_2 \tag{3}$$

in the areas other than containment penetration area [1], where

(σ_T) bending stresses due to thermal expansion

i stress intensification factors according to ASME Code, Section III, Article NC 3673

$[\sigma_A]$ allowable stress range for thermal expansion according ASME Code, Section III, Article NC 3611

However this methodology is based only on allowable stresses (first order type of analysis) and does not include the uncertainties due to the modelling assumptions, the material and statistical uncertainties. For these reasons the following reliability indices $(ri)_1$ and $(ri)_2$ are proposed

- for protection against plastic collapse

$$(ri)_1 = \frac{1.8[\overline{\sigma}] - 2[\Delta\sigma] - (\sigma)_2}{(\sigma_D)_2} \quad (4)$$

- for protection against pipe rupture

$$(ri)_2 = \frac{[\overline{R}_{1,2}] - 2[\Delta R] - \sigma_{eff}}{(\sigma_D)_2} \quad (5)$$

where

$[\overline{\sigma}]$, $[\overline{R}_{1,2}]$ median values of allowable stresses

$[\Delta\sigma]$, $[\Delta R]$ standard deviations of allowable stresses

Note, that the terms $[\overline{R}_{1,2}] - 2[\Delta R]$ resp $1.8[\overline{\sigma}] - 2[\Delta\sigma]$ represents the lower bounds of allowable stresses and that all quantities $(\sigma)_2$, σ_{eff} and $(\sigma_D)_2$ are calculated with respect to statistical distribution of key parameters.

3) RELIABILITY BASED IN-SERVICE INSPECTIONS METHODOLOGY

The main steps involved in the reliability based inspection planning methodology are shown in Fig. 1.

The first step is to identify all weldments and other critical cross sections (for example elbows) that need to be considered for inspection. The main criterion is the influence of corrosion-erosion effects. The next step is to perform the wall thinning predictions, for example for 10 years of operation. The first set of calculations is performed to obtain the probability of failure and reliability of indices $(ri)_1$ and $(ri)_2$ before any inspections are performed.

Due to the wall thinning effects the probability of failure increases as the piping gets older and the reliability indices decreases.

The criterion used for inspection is maintaining a minimum level of target reliability indices, for example 2.5. When the $(ri)_1$ or $(ri)_2$ reaches this value, an inspection is recommended. By inspecting knowledge is obtained about the past performance of the weldments or elbows which enables to update there confidence level. In the case where no crack or flaw is detected and the wall thinning effect is verified and statistically evaluated, it is possible to update the reliability curves to reflect the increased confidence, see Fig. 2. Where the new curves meets again the target reliability, the next inspection is recommended. One of the important parameters considered in this type of analysis is the uncertainly

associated with the inspection method used. The corresponding probability of detection curve must be modelled in the inspection updating analysis and it is supposed to be an important parameter. Also the wall thickness measurements direct influence the updated values of $(ri)_1$ and $(ri)_2$. The wall thinning decrease the inertia moment of the piping $I = \pi/64(D^4 - d^4)$ where D and d are the outer and inner diameter of piping, respectively. Due to corrosion-erosion effect the parameter d increases, particularly in elbows and bends. Our proposal is to measure the wall thinning with very fine steps along and around the elbow and for the calculation of I to use the lower bound of measured values. The effect of changes of ovality must be also taken into account.
The target reliability values and the probabilities of failure are very important parameters in this type of analysis. In accordance with International Atomic Energy Agency (IAEA) defence in depth (DiD) strategy, for steam piping and feedwater lines (Class 2 and 3 piping) of NPPs with Soviet WWER type reactors the scale according table T1 is proposed [2]. The numerical values must be agreed with safety authorities.

4) CONCLUSIONS

The reliability approach is not applied as an effective tool for nuclear pipework life management or life extension. Only in last years, there are first attempts to apply this methodology to NPPs maintenance. The opinions expressed in this paper only reflect the opinions of the authors. They are based on the IAEA Safety Issues Book. From this reason the ranking according defense in depth strategy takes the general character but the proposed target reliability indices values are specific only for NPPs with WWER type reactors. Their application to older plants is supposed to be a valuable tool for systematically incorporating the past inspection knowledges to enhance the nuclear safety and to plan future inspections more efficiently. The practical application to NPP Dukovany (4 units of WWER 440 MW, 10 years of operation experience) is now under discussion.

REFERENCES

1. US NRC, 1987. Relaxation in Arbitrary Intermediate Pipe Rupture Requirements. Generic Letter 87-11. June 19

2. IAEA, 1994. Ranking of Safety Issues for WWER 440 Model 213 Nuclear Power Plants. Extrabudgetary Programme on the Safety of WWER Plants. Report WWER-SC-108, Vienna, Austria.

Group	DiD classification	$(ri)_{1,2}$ target index	Probability of failure
A	Defense in depth is degraded	3	$\sim 10^{-5}$
B	Defense in depth is insuficient	2.5	$\sim 10^{-4}$
C	Defense in depth is unacceptable	2	$\sim 10^{-2}$

Table T1

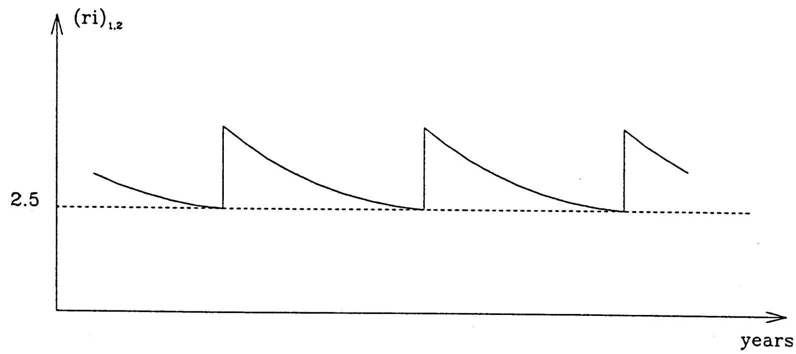

Fig. 2