Leak Failure Analysis of the Stainless Steel Narrow Gap Welds in Nuclear Power Plant Piping

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Abstract

Over the years, the use of risk information in safety assessment of nuclear power plant has been gradually increased. For example, the risk information, or failure probabilities are used in the risk-based inspection. In this paper, the leak failure probabilities of the narrow gap welds joining thick stainless steel pipes were evaluated. The base metal parts were also analyzed for comparison purpose. The effect of in-service inspection on the failure probability of these parts was investigated as a part of current regulatory requirements. Materials used in this study are 316L and ER 308L for the base metal and the narrow gap welds respectively. Various crack sizes and aspect ratios were assumed and both circumferential and axial directions were considered. Variations in leak and break probabilities of different weld zones and base metal were observed.

1. Introduction

Thermal fatigue is the major ageing mechanism particularly for surge, spray and branch lines and their nozzles that are subjected to thermal transients during plant startup/shutdown, thermal stratification, thermal shock, turbulent penetration, and thermal cycling. Many leak events (0.004 – 110 gpm) caused by thermal fatigue cracking of nozzle welds of PWR reactor coolant pipes have been reported in various countries [1].The narrow gap welding (NGW) technique is being applied to produce butt welds in several locations in the nuclear piping system. Cracks located at the inner surface of the weld will gradually propagate through the thickness direction under fatigue loading. The variations in mechanical properties of different zones of the weld as well as base metal might show different leak failure probabilities which should be minutely investigated as per the present regulatory requirements [2]. Most of the leak and break failure analysis were performed in past did not consider the spatial variation of the mechanical properties along the weld. In this study, the leak and break failure probabilities of the stainless steel narrow gap welds and base metal sections were evaluated at 320°C. Special attention was paid to evaluate the spatial variation of the failure properties and their dependences on the different in-service inspection intervals.

2. Development of a Probabilistic Computer Code

The probabilistic fracture mechanics (PFM) approach is a useful tool for determining failure probabilities (P_f) of structural components by varying reactor operating conditions e.g. operating internal pressure, dead weight stress of components, thermal stress; structural geometries e.g. pipe diameter, pipe thickness and material properties e.g. flow stress, fatigue constants, fatigue exponents, etc. The Monte Carlo simulation method has been used in this paper. The probability that the weld has failed at or before time t, $P(t_f \le t)$ can be determined by Eq. (1)

$$P(t_f \le t) = \sum_{m=1}^{M} \frac{N_{F,m}(t)}{N_m} p_m \qquad (1)$$

where M is the total number of cells, N_m is the number of samples from the m-th cell, $N_{F,m}(t)$ is the number of samples taken from the m-th cell which have failed at or before time, t, p_m is the probability of an initial crack having dimensions within the region of the m-th cell. The piping integrity evaluation program based on PFM was developed using Microsoft Visual Basic 6.0. Fig. 1 shows the program window that consists of input material property part, reactor operating condition part, constants part, the controlling part, i.e. cell size, iteration/simulation number and the output result part. The code was also run to see the effects of preservice and inservice inspection on failure probabilities.

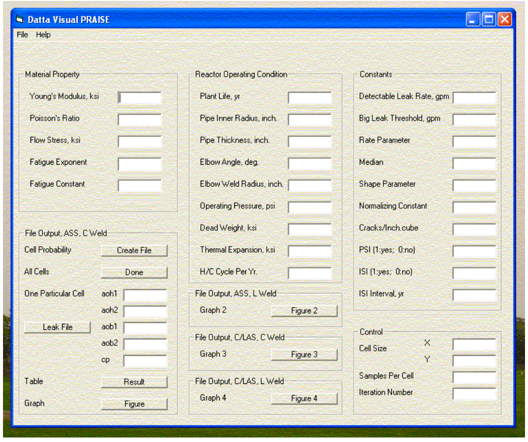

Figure 1. Input sheet of the code (austenitic stainless steels, carbon and low alloy steels with weld/base metal sections).

3. Results and Discussions

The weld section (316L base metal, ER 308L weld metal) near RPV inlet nozzle in a typical PWR plant was chosen for this research work to find out the variations of cumulative small leak, big leak and loca failure probabilities for the sixty years of plant's life. All these reference input data were taken from today's standard light water reactor primary piping system. For conservative analysis the maximum level of input stresses were considered to find out the relative cumulative failure probabilities for the sixty years of plant's life depending on components geometry, material mechanical properties and material dependent marginal probability of crack detection [3]. The narrow gap weld zone shows the highest cumulative small leak failure probabilities on the order of about 2.33×10^{-7} considering the weld root part's flow strength and fatigue crack growth properties.

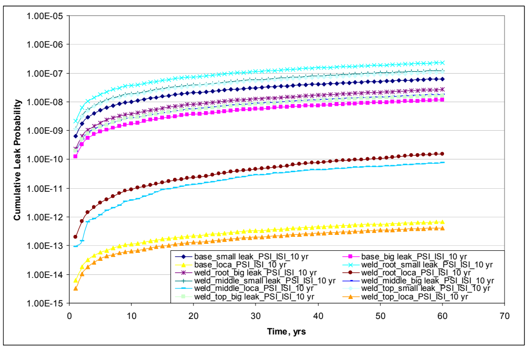

Figure 2. Leak and break failure probabilities of stainless steel narrow gap weld and base metal considering variations in strength and fatigue growth rate at different locations.

In case of base metal this is on the order of 6.23×10^{-08} . The effect of pre-service inspection and the regular ten years inservice inspection were considered in all cases. The preservice inspection has the higher effect to reduce the leak and break failure probabilities than the in-service inspection program. Considering the most conservative marginal probability of detection curve the regular ten years in-service inspection reduces the leak and break failure probabilities up to 20% at the sixty years of plant's life which is insignificant, but improving the inspetion efficiencies these reduction of failure probabilities could be enhanced.

4. Conclusions

The failure probabilities of subcomponents of a PWR coolant loop were evaluated using PFM approach. Based on the evaluation, the following conclusions were drawn:

- Although the strength of the weld metal is equal or higher than the base metal, the leak failure probability of weld metal was higher than the base metal.
- Considering the flow strength and fatigue crack growth rate of the root part of the narrow gap weld zone for conservatism, the highest small leak and break failure probabilities for circumferential weld are $\sim 10^{-7}$ and 10^{-10} respectively.
- For both narrow gap weld and base metal sections, ten years regular in-service inspection reduces the failure probabilities up to 20% considering the marginal probability of detection curves.

Acknowledgements

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