Acceptance criteria for cracks in control rod drive penetration at reactor vessel head

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ABSTRACT: The aim of one of the activities of a Research Program undertaken in Spain was to be ready to evaluate possible cracks detected during in-service inspections in control rod drive penetrations at reactor vessel head (Tecnatom, 1994). This paper describe the acceptance criteria developed for defects in these components.

1 INTRODUCTION

The presence of cracks, in control rod drive mechanism (CRDM) penetrations was first detected in certain French Plants. As is well known, the cause of this cracking is primary water stress corrosion cracking affecting the area of the weld between the penetration and the vessel closure head.

A research program was undertaken in Spain to deal with the treatment of this problem, which might affect certain of the country’s plants.

Generally speaking, the following requirements are to be met in establishing acceptance criteria for defects in these components:
- Maintenance of adequate safety margins with respect to rupture of the penetrations.
- Prevention of leaks during normal operation, which might lead to corrosion of the outer wall of the penetration and of the ferritic steel of the reactor vessel closure head.

The analysis of which the defects acceptance criteria are based are as follows:
- Elastic-Plastic stress analysis of the CRDM penetrations.
- Determination of maximum permissible defect sizes.
- Determination of crack growth rate.

In order to validate the analytical methods, an experimental program was scheduled within the framework of the aforementioned research project.

2 ELASTIC-PLASTIC STRESS ANALYSIS OF THE CRDM PENETRATIONS

These control rod drive mechanism (CRDM) penetrations are characterized by their robust design, such that under normal operating conditions the stresses caused by operational pressure and temperature loads are not sufficiently great so as to came the deformations (ovaling and bending) measured at certain plants. The aforementioned deformations are to be attributed to the residual stresses in and near the weld region due to the welding process. Stresses exceed the yield strength of the Alloy 600 weld and penetration material. Therefore elastic-plastic stress analysis has been carried out
in such a way as to suitably reproduce the load history of the penetration which leads to the accumulation of plastic deformations.

The analyses were performed for the central penetration (aximetric two-dimensional model) and for one peripheral penetration (three-dimensional model) using the finite elements technique. The three-dimensional model of the peripheral penetration is shown in figure 1. The CRDM penetration tube, the adjacent section of the vessel head, butting and the joining weld were modeled. The penetration tube and weld metal were modeled as Alloy 600 and the vessel head as carbon steel with temperature dependent mechanical properties. Stress-strain material properties with kinematic hardening were used.

The load history applied to the model is listed below:
- Thermal loads from welding process (two pass).
- First hydrostatic test (loading and unloading).
- Second hydrostatic test (loading and unloading).
- Normal operating loads

The stresses caused by each of the loads were stored and maintained as the initial stress to the next load to simulate the accumulation of plastic deformations and stresses.

Thermal analysis simulating the welding process was performed to obtain the temperature distribution followed by the stress analysis. All model elements were set to be stress-free at room temperature, with the exception of the weld elements which were set to be stress-free at 1,370 °C (near Melt point). Butting elements were set to be stress free at intermediate temperature to avoid exaggerated thermal stresses. These stress-free reference temperatures simulate the weld shrinkage due to cool-down. Results of analysis show that the center penetration has lower hoop and axial stresses than the outer penetration.

The hoop, axial and equivalent (Von Mises) stresses for the steady state operating conditions on the inside surface of the outer penetrations at center side and hillside of the vessel head are shown in figures 2 y 3.

The highest hoop stress occurs just below the weld on center side of the penetration (Figure 2).

Axial stress are always lower than hoop stress at all locations.

These results are consistent with the location and orientation of reported inspection cracks at certain plants (i.e. axial cracks near the weld).

Likewise, and noticing the large extent to which the residual stresses of the welds affect the stress status of the CRDM penetrations, measurement of these residual stresses was performed on a real-scale mock-up of a peripheral penetration to validate the numerical methods used in simulating the weld process. From a qualitative point of view there is a good agreement (Figure 4) between tests and analytical results (ENSA, 1994). More conservative analytical stresses might be due to differences in materials properties and the hypothesis used with the numerical methods to obtain conservative results.

3 DETERMINATION OF MAXIMUM PERMISSIBLE DEFECT SIZES

The maximum permissible defect sizes have been determined using the limit load concept (net section collapse). The maximum permissible defect sizes have been determined in accordance with requirements of article IWB-3640 and Appendix C of Section XI of the ASME code. These criteria are based on the limit load concept (Net section collapse) and are applicable to materials exhibiting highly ductile behaviour, such as austenitic steels and Ni-Cr-Fe Alloys such as Inconel-600.

In the case of axial cracks at and above the weld the maximum permissible depth is 75% of wall thickness. It should be pointed out that this permissible depth is
conservative, since the penetrations in question are surrounded by the vessel head which prevents radial expansion, and consequently the initiation of unstable propagation of axial cracking. The effect of the remaining thickness should be interpreted as relating more to leak development than to structural issues.

Axial cracks below the weld are acceptable regardless of depth. Cracks in this area have not leakage significance and 100% of wall thickness is acceptable. Axial cracks below the weld which extent through and/or above the weld are limited to depth of 75% of the wall.

4 CRACK GROWTH RATE

In order to determine the acceptability of a crack it is necessary to accurately assess its evolution during the plant operating. The cause of crack extension is primary water stress corrosion cracking (PWSCC) and the loading of interest is the steady state operating condition.

The results of the stress analysis of the peripheral penetration were used in the flaw tolerance evaluation.

From the defect acceptability point of view the relationship between crack growth rate and the stress intensity factor $K_I$ is of particular interest. The relationship used has been established by means of the Scott equation (Scott 1991), with certain temperature corrections. This equation at 330°C is

\[ \frac{da}{dt} = 2.8 \times 10^{-12} (K_I - 9)^{1.16} \frac{m}{s} \]

where $K_I$ is the applied stress intensity factor in MPa $\sqrt{m}$. Crack growth rate is affected by temperature, and therefore a temperature adjustment is necessary. The maximum operating temperature at Spanish Plants is 320 °C and the following correction of the Scott model was used:

\[ \frac{da}{dt} = 1.78 \times 10^{-12} (K_I - 9)^{1.16} \frac{m}{s} \]

In view of the importance of this issue, a specific testing program was performed within the framework of the aforementioned research program. Results of this testing program show a conservative growth rate prediction using the Scott model at 320 °C.

For surface axial cracks the stress intensity factor was calculated using the Newman-Raju expression (Raju and Newman):

\[ K_I = \sqrt{\pi \frac{a}{Q}} \sum_{j=0}^{3} G_j A_j a^l \]

This expression was used for two different form factors $l/a = 2$ and $l/a = 6$, where $l$ is the crack length and $a$ is the crack depth. Conservative crack growth rates were obtained for $l/a = 6$. Generally speaking the greater form factor the greater the crack propagation rate.

For a through-wall crack the stress intensity factor was calculated using the expression for a through-wall crack in a plate.

\[ K = \sigma \sqrt{\pi a} \]

The Scott equation (2) is solved by means of an iterative method to obtain the crack remanent lifetime. The time for the detected crack to reach the allowable crack size (75% of wall thickness) determines the remanent lifetime. Figure 5 shows the remanent lifetime for surface cracks postulated in the highest stress location.
5 CONCLUSIONS

Results of the stress analysis are consistent with the axial orientation and location of cracks which have been found in certain plants. The maximum permissible depth is 75% of wall thickness at end of cycle. This maximum depth should be interpreted as relating more to leak development than to structural issues.

Acceptance criteria are ready to evaluate possible cracks detected during inservice inspection, maintaining adequate safety margins.

6 REFERENCES


Figure 1: Finit Element Mesh
Figure 2: Stress distribution vs distance from the bottom of CRDM. Center side.

Figure 3: Stress distribution vs distance from the bottom of CRDM. Hill side.

Figure 4: Residual stress distribution.
REMANENT LIFE TIME FOR SURFACE CRACKS IN A CRDM - CENTER SIDE (180°)

Figure 5: Remanent lifetime for surface cracks. Center side (180°).