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Life assessment of alloy 600 RPV penetrations

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ABSTRACT

In September 1991, during a hydrotest, a leak was detected on the vessel of Bugey3, a 3 loop French PWR plant. The leak was due to a through wall crack in the Control Rod Drive Mechanism (CRDM) nozzle. PWSCC of Alloy 600 was identified and, due to large number of French plants with a similar design, an extensive program was decided on different topics :

- safety evaluation,
- in-service inspection,
- mechanical evaluation of residual life,
- material properties,
- design of future plants.

This paper presents the status of this work in the beginning of 1995 and how we extend the work to other RPV penetrations.

1 - INTRODUCTION

In September 1991, during a hydrotest, a leak was detected on the vessel of Bugey3, a 3 loop French PWR plant [1]. The leak was due to a through wall crack in the Control Rod Drive Mechanism (CRDM) nozzle[1]. PWSCC of Alloy 600 was identified and, due to large number of French plants with a similar design, an extensive program was decided on different topics :

- safety evaluation,
- in-service inspection,
- mechanical evaluation of residual life,
- thermohydraulic considerations of the upper part of the vessel,
- material properties [2],
- mitigation and repair process,
- design of future plants,
- general maintenance program [3], ...

The Bugey3 crack was linked to :

- high temperature of the vessel head (315°C),
- high residual stresses on the inner surface due to the welding process of the penetration with the vessel head (without stress relieve) ,
- sensitivity to PWSCC of Alloy 600.

This paper is focused only on the life evaluation of Reactor Pressure Vessel penetrations :

- stress evaluation,
- material properties,
- sensitivity studies to determine the main governing parameters,
- validation through a mock-up progam.

2 - STRESS EVALUATION IN CRDM NOZZLES

The first preoccupation was the stress level on the inner surface of the different type of CRDM nozzles during operation in order to analyse crack initiation, and the second was the stress distribution through the thickness in order to analyse crack growth rate.

2.1 - STRESS LEVEL ON THE INNER SURFACE

Two types of geometries were mainly studied :

- central configuration,
- hill-side configuration (45° inclined)

Figure 1 presents the main dimensions of the penetrations and the different materials used. All the penetrations are cold shrinked and welded without stress relief for alignement considerations. Before operation, the conventional hydrotest at 22.8 MPa was done on the entire Reactor Pressure Vessel (RPV) .

The numerical simulations were done in 4 steps :

- cold shrinking (0.08 mm on the diameter),
- welding process with different models,
- cold hydrotest,
- service conditions (15.4 MPa, 315°C) .

The first computations were done on a central configuration using a two-dimensional finite element model and mean values for material properties : yield strength for Alloy 600 360 MPa and for base metal 485 MPa.

The stresses were obtained by cooling down the model from the maximum temperature during the welding process to room temperature by elasto-plastic finite element computation.

The main available data to validate the stress evaluation are the profilometry measurements done on vessels during manufacturing, the maximum measyed inner radius increase is 0.17 ± 0.04 mm while the simulation results are : 0.24 mm leading thus to a slight conservatism in the stress evaluation.

The residual stress evaluation follows the cold shrinking simulation with contact elements between vessel head and penetration and is followed by cold hydrotest and operating condition simulation.

The results are presented step by step on table 1. These results show :

- maximum stress values during operation (300 MPa),
- circumferential stresses slightly higher than longitudinal stresses,
- stresses under the weld slightly higher than above the weld,
- a beneficial effect of hydrotest,
- stress level higher at the end of fabrication than during normal operation,
- a slight opening over the weld on a span of 5 mm during hydrotest and normal operation.

Similar work has been done on hill-side nozzles. The major differences is the welding process simulation based on an imposed deformation of -1.45% applied to the weld with a specific weld cross section surface correction.. The value has been derived from a two-dimensinnal model that leads to an inner radius increase of 0.18 mm, the results are compared in terms of ovalisation, position of the maximum ovalised section and deflection at the bottom of the penetration.

The comparisons are presented in table 2 and the stress levels in table 3. They show :

- two peaks in inner surface stress distribution downhill and uphill (0 and 180°),
- during operation conditions, the circumferential stresses are higher than the longitudinal stresses and the maximum value is 495 MPa,
- stress level higher at the end of fabrication than during normal operation,
- the stresses are higher in the hill-side than in the central configuration during normal operation.

2.2 - SENSITIVITY STUDIES

The major mechanical parametrical studies, presented in [5], have considered : the cold shrinking modelisation, material properties, counterbore effect, closing vessel head proximity, nozzle position on the vessel head and different welding process models (single pass / multi pass, volume of the weld). The major mechanical parameters are the nozzle set up angle, the volume and the shape of the weld and the welding process simulation.

The major metallurgical parametrical studies are presented in [6] and [7]. The penetrations were manufactured from Electroslag Remelted ingots in Alloy 600. The analysis of cracked nozzles from plants or laboratory tests leads to define a PWSCC criteria.for crack initiation based on manufacturing process (Table 5) : tensile properties after forging (before heat treatment) and heat treatment temperature . The comparison of In Service Inspection (ISI) results with the sensitivity criteria confirms a good agreement.

3 - CRDM MOCK-UP PROGRAM

Seven corrosion tests have been performed on scale 1 CRDM nozzle mock-ups at 350°C in caustic solution environment (the threshold stress value for these tests are between 300 and 350 MPa for crack initiation). The different geometries or test conditions are presented in table 4. Three mock-ups are repeated for residual stress measurements by hole drilling technique.

The main conclusions of this progam are :

- no cracks initiate in the central nozzle,
- no circumferential cracks initiate in any nozzles,
- few longitudinal cracks initiate at down-hill (0°) and up-hill (180°) that confirms the higher values of the stresses in the circumferential direction,
- few longitudinal cracks in a 32° angle nozzle that confirms a stress level higher than 350 MPa on these intermediat nozzles,
- a higher level of stresses in the couterbore area,
- the computation of the stress level,using the models presented in the previous paragraphs (without hydrotest) , is too conservative for the central configuration and reasonable in the hill-side.configuration using multipass modelling of the welding process.

The comparison between residual stresses measured by hole drilling technique and computed stresses comfirms the conservatism of stress evaluation for central penetration and some differencies, that aren't completly explained for hill-side penetration (reasonable for up-hill region, but not so good for down-hill region)

4 - FLAW EVALUATION

Different analyses have been done : crack initiation, critical crack sizes and crack growth analysis.

For the central penetration, the time to crack initiation is larger than the plant life for longitudinal and circumferential crack above the weld, but around 20 equivalent full power years (EFPY) under the weld for hot temperature plenum (315°C). For hill-side situation, the time to crack initiation can be short (around 5 EPFY) ; but, the first location is clearly under the weld, at 180° (up-hill) for longitudinal cracks.

Through wall critical cracks were considered. Due to high toughness of the material (J_{IC} greater than 1000 kJ/m^2) and low primary loads, the critical crack sizes are large : 350 mm above the vessel head for longitudinal crack and 90% of the thickness (13.5 mm for 15 mm thick penetration) or 90 % of the circumference for circumferential part-through and through cracks.

To analyse the crack growth rate, we used the elasto-plastic stress evaluation previously presented and crack growth curves for alloy 600 under PWR environement [4] :

$$da/dt = 2.8 \times 10^{-12} (K-9)^{1.16} \quad \text{at } 330°C$$
$$\text{with : } da/dt \text{ in m/s and K in } MPa.m^{0.5}$$

To take into account the scatter in the experimental results we increased the da/dt by 15%; however, to account for cold hardening and temperature effectects (from 330° to 315°C), we divided the da/dt by a factor of 2, this results in an upper bound crack growth of 4.4 mm per year.

For the central penetration, the longitudinal cracks cannot significantly grow in the axial direction due to cold shrinking stresses in the vessel head and the circumferential cracks don't initiate during the plant life.

For hill-side penetration, the longitudinal cracks can grow from the inner surface through the thickness for up-hill side (180°) in few years (around 7 EFPY) and for down-hill side (0°) in a shorter time (around 4 EFPY).

5 - BOTTOM INSTRUMENTATION NOZZLE EVALUATION

The first approach is to compare the major parameters :

- geometries (figure 1),
- in-service temperature,
- material properties,
- stress level.

All these comparisons confirm that BMI nozzles are less sensitive than CRDM nozzles: lower temperature, lower yied strenght, lower stress level mainly due to stress relieve during fabrication.. Neithertheless, we try to quantify theses differencies by different stress measurements, stress evaluation by finite element computations and a specific mock-up program under caustic environment. All the preliminary results of this ongoing program confirm the first evaluation.

6 - CONCLUSIONS

A large mechanical program has been undertaken to analyse the complex stress field during operation and test conditions. The agreement with measurements and ISI crack locations are not completely satisfactory, but the main governing parameters are clearly identified : the circumferential stress level on the inner surface in front of the weld, the in service temperature , the yield strength of the material the setup angle of the nozzles and the sensitivity of the material.

The flaw evaluation resulted in the large critical crack size for through wall cracks. The crack growth rate of Alloy 600 from the material properties point of view is under confirmirmation by in service inspection results on cracked nozzles.

The only phenomenon not taken into consideration in these approaches is the inner surface finishing which requires simulation of a strain hardened surface layer i.e. a different material.

For BMI nozzles a similar work is under progress, but due to lower temperature and lower stress level, their sensitivity to stress corrosion cracking is lower than CRDM nozzles.

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Figure 1 : Main dimensions of French CRDM and BMI nozzle

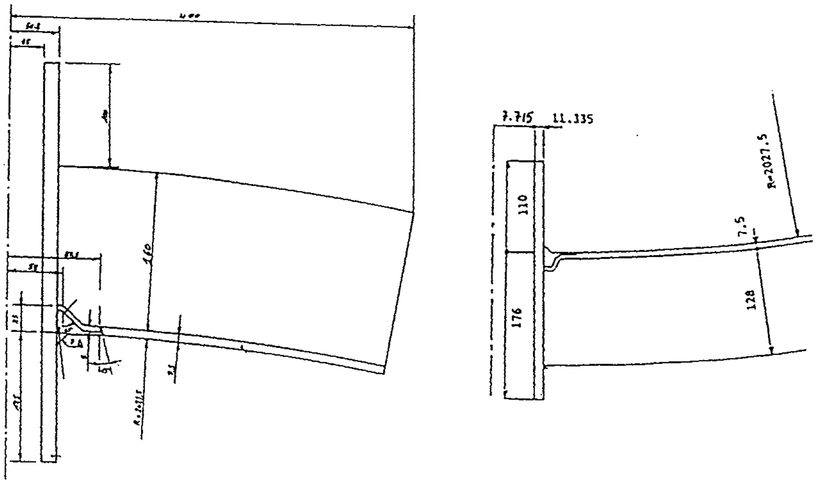

Table 1 : Longitudinal and circumferentiel stresses in a central CRDM nozzle

maximum stress MPa	after welding	after hydrotest	in operation
circumferential	450	350	310
longitudinal	310	300	300

Table 2 : Comparison between measured and computed values

	measured	computed
maximum ovalisation (mm)	1.5	1.8
position of maximum ovalisation (mm from the bottom of the penetration)	100	170
deflection (mm)	1.4	0.88

Table 3 : Longitudinal and circumferentiel stresses in a hill-side CRDM nozzle (45°)

Maximum stress MPA		down-hill 0°		up-hill 180°	
		above the weld	under the weld	above the weld	under the weld
end of welding	circumferential	570	408	---	510
	longitudinal	591	160	90	283
after hydrotest	circumferential	275	382	---	464
	longitudinal	471	157	109	246
normal operation	circumferential	407	395	---	495
	longitudinal	446	174	129	283

Table 4 : Mock-up test matrix

Configuration	**counterbore**	**angle**	**ovalisation (mm)**	**concentration (g/l)**	**remarks**
central	no	0°	0.11 0.06	100	capsule residual stress
hill-side (BUGEY 3)	85mm cylindrical	0°	0.96 1.17	4 100	autoclave capsule
hill-side (T54 BUGEY 3)	95mm cylindrical	39°	1.05 0.96	4	capsule residual stress
hill-side (FSH)	no	39°	0.91	4	capsule
intermediate (CP0)	70mm cylindrical	32°	0.65	100	capsule
hill-side (4 loops)	conical	47°	1.62 1.73	100	capsule residual stress

Table 5 : PWSCC sensitivity criteria

Tensile Properties	Heat Treatment Temperature	Sensitivity
Yield strength < 535 MPa and Elongation > 28%	720°C	Low
Yield strength > 535 MPa or Elongation < 28%	720°C	Intermediate
Yield strength < 535 MPa and Elongation > 28%	820°C	Intermediate
Yield strength > 535 MPa or Elongation < 28%	820°C	High