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Analysis of defects in stainless steel piping

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1. Introduction

The piping made of stainless steel are commonly used in power plants. The stainless steel has good resistance to corrosion and it almost does not rust or corrode. Therefore the stainless steel is used for major piping such as main circulation circuit (MCC).

Despite all the positive properties of the stainless steel it has also an imperfection. The problem was at welded joints of austenitic stainless steel piping. The weld start to crack from the inner surface of the pipe at the welded joints heat effected zone. This phenomenon was called Inter Granular Stress Corrosion Cracking (IGSCC). The first cracks were detected at nuclear power plants of the USA in the late sixties of twentieth century. In the middle of the seventies the Western countries and Japan have declared about cracking of the primary circuit piping made from austenitic stainless steel of boiling water reactors (BWR) and pressurised water reactors (PWR). At RBMK type reactors in Russia the first IGSCC cracks were observed in the middle of the nineties. After detection of IGSCC in Russian NPPs, the extended planned preventive maintenance of austenitic stainless steel piping of MCC of Ignalina NPP was performed and existence of IGSCC was confirmed.

IGSCC is a combination of the following three factors: material, stresses and environment. All these factors are important for cracking.

In 2000-2001 performed IAEA Extra budgetary Programme on Mitigation of IGSCC in RBMK Reactors an engineering judgement on the parameters affecting the observed cracking is given based on received information and on previous experience and knowledge [1]. The main root causes of IGSCC in the stainless steel of type 08X18H10T can be summarised as follows:

- sensitisation, which is caused by a high degree of free carbon and a low stabilisation ratio in the material and high heat input during welding;
- deformation of the pipe inner surface due to weld preparation;
- geometrical weld imperfections accelerating crack initiation;
- deformation of the material in the heat affected zone (HAZ) due to weld shrinkage;
- high tensile stresses (residual and/or operational), indicated by a large opening of the cracks;
- environmental parameters, indicated by chlorides on the fracture surface, known condenser leakage incidents, possible sulphate intrusions, which cannot be ruled out, water impurities and the oxidising power of the water;
- operational fluctuating stresses indicated by observation of fatigue striations on the fracture surfaces.

The IGSCC cracks in MCC austenitic piping of Ignalina NPP appear at the inner surface in HAZ near to weld root and grow to outside close to fusion line (Fig. 1) [1]. The HAZ material is susceptible to IGSCC and sensitised in most cases. The sensitisation occurs due to overheating during welding and is an important factor in the cracking behaviour.

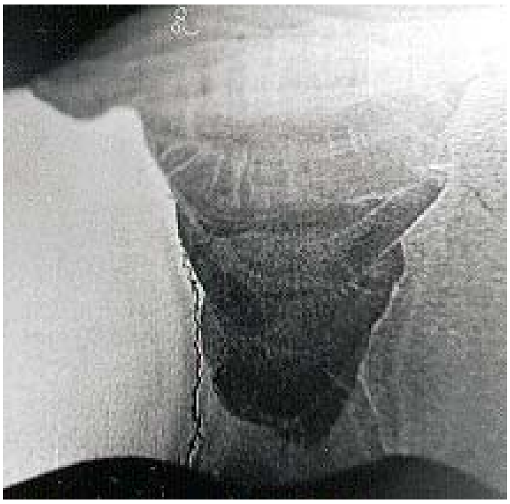

Fig. 1 IGSCC of piping welded joints heat affected zones

According to investigations, the crack growth stops reaching zone of low sensitisation approximately in the middle of pipe wall. It determines the maximal height of detected cracks of 8-10 mm. However, it is necessary to mention that is not known with a certainty if only degree of sensitisation stops a crack grow. If one waits long enough without inspections there are no guaranties that the crack will not penetrate the wall thickness. Up to now no leakage has occurred.

IGSCC is one of the main degradation mechanisms in the austenitic stainless steel piping in RBMK type reactors. Therefore it is important to evaluate defects in piping and to show NPP safety level. During the last planned preventive maintenance in August-September 2008 126 IGSCC cases, which had to be analysed, were identified in 325 mm outside diameter austenitic stainless steel piping in Iganlina NPP unit 2 [2]. Analysing detected defects it is important to evaluate their acceptability and growth during operation.

In Lithuania there are one decommissioned Ignalina NPP. Ignalina NPP has two units with RBMK-1500 type reactors. The first unit was stopped in 2004 and the second at the end of 2009. Such defect evaluations are necessary in the operating nuclear power plant to avoid the leakage of the coolant of reactor but it is also important at the stage of decommission. These piping later will be used for decontamination of the reactor.

2. Methodology for evaluation of cracks

Evaluation procedure of IGSCC defects in MCC of RBMK type reactor consists of two parts. The first part is the evaluation of defect if this defect is in safe margins and the second part consists of crack growth calculation.

The defects in the MCC were detected using ultrasonic nondestructive testing method during planned preventive maintenance in August-September 2008. It was done by the NPP staff.

The evaluation of detected defects was made by R6 method option 1 [3] (Fig. 2). The R6 option 1 based only on yield and tensile strength values and leads to the most conservative assessment. This method was developed by Nuclear Electric plc [4]. The main idea of this method is that the crack is described by two variables K_r and L_r. Variable K_r is the relation between the stress intensity factor [5] and the factor witch specifies the material resistance to crack growth. Variable L_r is the relation between the applied load and materials plasticity limit. The variation of these two variables is presented in the Fig. 2.

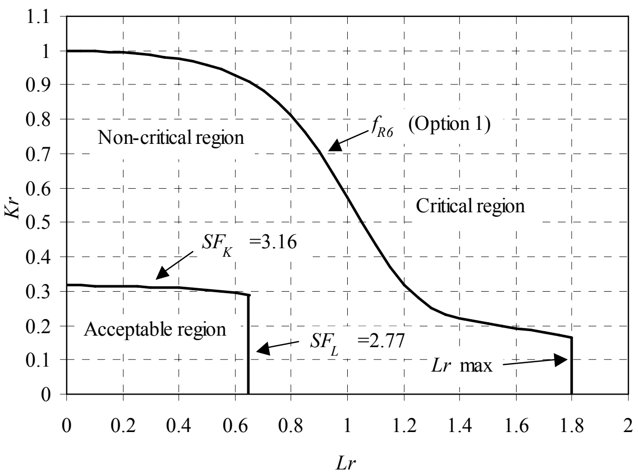

Fig. 2 R6 method

If the calculated value is in the region surrounded by coordinate axes and f_{R6} and $L_r\,max$ curves (non-critical region) the existing crack will not initiate the growth. However if the calculated value is outside this region the crack will grow and material can brake down. The acceptable region is the noncritical region just considering the safety factors. According the methodology [6] safety factors $SF_K = \sqrt{10}$ and $SF_L = 2.77$ should be used.

The f_{R6} and $L_r\,max$ curves are calculated using the following equations

$$K_r \le f_{R6} = \left(1 - 0.14L_r^2\right)\left[0.3 + 0.7\,exp\left(-0.65L_r^6\right)\right], \quad (1)$$

$$L_r \le L_r\,max = \begin{cases} 1, & \text{For materials with yield plateau} \\ \dfrac{\sigma_f}{\sigma_Y}, & \text{For all other cases} \end{cases} \quad (2)$$

where σ_f is flow stress, σ_Y is yield strength.

The crack growth calculation is made by the methodology described in [6]. The crack growth calculation was performed for 1.5 years, i.e. until shut down of the reactor. The evaluation of the crack after shut down until decontamination should be performed also. One year has 8750 hours (1.5 years = 13125 hours). According this methodology to determine the crack growth caused by IGSCC mechanism the following equation was used (when $K_I < 50$ MPa$\sqrt{\text{m}}$)

$$\frac{da}{dt} = 4.5x10^{-12}\left(K_I\right)^3, \quad (3)$$

where da/dt is crack growth speed, mm/s; K_I is stress intensity factor, MPa$\sqrt{\text{m}}$.

This equation describes the upper boundary of experimental data for welded joints of austenitic piping in BWR type reactors in Sweden [6]. According to the exploitation experience and experimental data for welded joints of piping made of 08X18H10T steel working in water surrounding in RBMK type reactors proves that crack growth speed due to IGSCC mechanism is not bigger than 1 mm per year [7 - 9].

The comparison of the crack growth speed data [10] showed, that Eq. (3) gives conservative evaluation of crack growth rate in MCC in RBMK reactor.

According this Lithuanian regulatory add the statement to [6] requirements which says that crack growth speed, when depth of the crack reaches the 50% of the pipe wall thickness, should be 1 mm per year.

The crack growth due to fatigue was evaluated by the following equation

$$\frac{da}{dN} = 4.0x10^{-8}\left(\Delta K_I\right)^{2.6355}, \quad (4)$$

where da/dN is crack growth speed due to fatigue, mm/cycle; ΔK_I is threshold stress intensity factor and it was used of 5.4 MPa$\sqrt{\text{m}}$ [6]. It is taken that one year of operation contains 30 load cycles.

3. Calculation and results

The crack evaluation due to IGSCC mechanism and crack growth calculations were made using computer program SACC 4.0 [5].

The evaluation objects are the defects detected in the MCC of RBMK type reactor (Fig. 3). This piping is made of 08X18H10T austenitic stainless steel. The used mechanical properties of this steel are presented in Table [6, 10], here T is temperature, E is elastic modulus, ν is Poisson's ratio, σ_Y is yield stress, σ_U is tensile strength, K_{IC} is critical stress intensity factor. The outside diameter of the pipes is 325 mm and the wall thickness – 16 mm. As it can be seen from Table the worst material properties at working temperatures are in main material. To be more conservative material properties of the main steel were chosen for evaluation of detected defects.

Table

Mechanical properties of 08X18H10T austenitic stainless steel [6, 10]

	T, °C	E, MPa	ν	σ_Y, MPa	σ_U, MPa	K_{IC}, MPa$\sqrt{\text{m}}$
Main steel	20	1.40x10^5	0.35	309	608	126
	285	1.40x10^5		232	397	97
Weld metal	20	1.52x10^5		348	627	137
	285	1.40x10^5		221	464	108
Thermal effected zone	20	1.40x10^5		283	584	118
	285	1.89x10^5		240	474	133

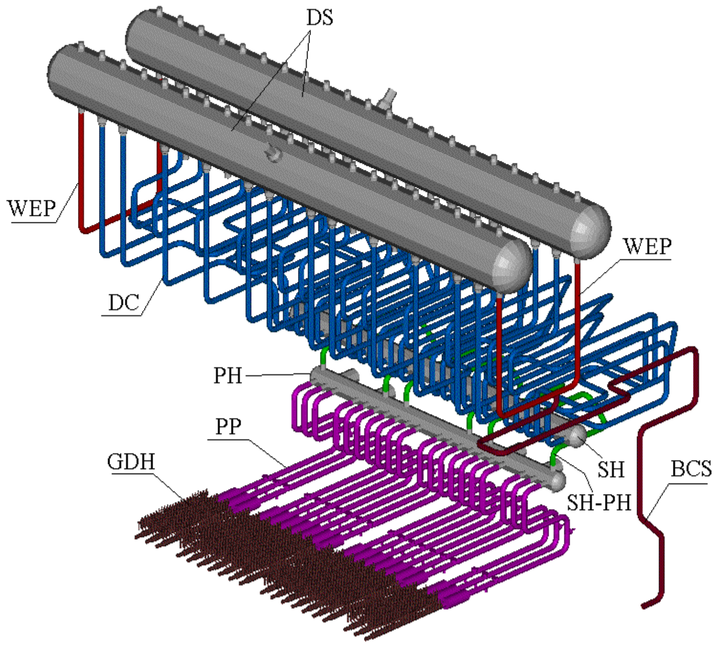

Fig. 3 Main circulation circuit (MCC) austenitic piping of one loop (WEP – water equalizing piping; DC – downcomers; SH-PH – bypass between suction header (SH) and pressure header (PH); PP – pressure piping, connecting pressure header (PH) and group distribution header (GDH); GDH – group distribution headers; BCS – blowdown & cool-down system piping)

As it is seen from Fig. 3 the piping system is quite complicate. Therefore the load combination of dead weight and pressure, membrane stress and thermal expansion is different in each particular place. The load combination to each weld was calculated in Report No. 10048500-3 [11].

During planned preventive maintenance 126 defects were detected by ultrasonic nondestructive method in the MCC in 2008 [2]. All 126 defects were evaluated using the methodology described in chapter 2. In case of big amount of defects and calculation data only few of them were presented in this paper. Only defects where the biggest load combination occurs and the deepest defect are shown. The evaluation results of detected defects in the SH-PH (bypass between suction header and pressure header) piping are shown in Fig. 4.

Evaluated cracks are presented by point in this figure. Four defects were detected in this section of piping. The depth and length of the first defect respectively was 2 mm and 50 mm, for the second 2 mm and 70 mm, for the third 2 mm and 40 mm and for the forth 3 mm and 40 mm. The stresses level in welds where these defects were detected are: the primary membrane stress S_m = 36.5 MPa, the primary bending stresses due to pressure and dead weight $S_b(p)$ = 10.9 MPa, the bending stress due to thermal expansion $S_b(T)$ = 55.1 MPa.

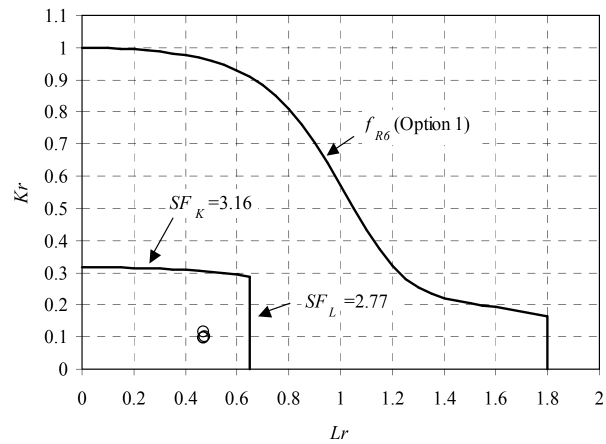

Fig. 4 Evaluation of cracks in the SH-PH piping

The biggest defect detected during this inspection was in downcomers (DC). This crack was 54 mm long and 10.5 mm depth. The stress in this defected level are S_m = 30 MPa, $S_b(p)$ = 3.4 MPa and $S_b(T)$ = 25.3 MPa. The evaluation of this crack is shown in Fig. 5. Evaluated cracks are presented by point in this figure.

Crack growth calculation due to fatigue showed that after 1.5 years (45 load cycles) all detected defects will grow not more than 0.01 mm.

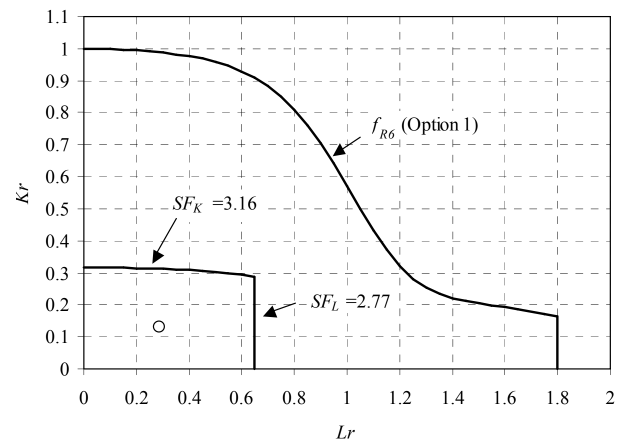

Fig. 5 Evaluation of crack in DC

Crack growths due to IGSCC mechanism for detected defects in the SH-PH piping are shown in Fig. 6. As you can see in the figure detected defects were 2 mm and 3 mm depth. The growths of defects until they reach ½ pipe wall thickness were calculated using Eq. (3). The defects with initial depths of 2 mm ½ pipe wall thickness reach after 10324 hours (1.18 years) and the defects with initial depth of 3 mm reach it after 9943 hours (1.14 years). When the defects reach ½ wall thickness the defect depths growth speed slows down (as it was explained in chapter 2) and after 1.5 years of exploitation will respectively reach 7.82 mm and 7.86 mm.

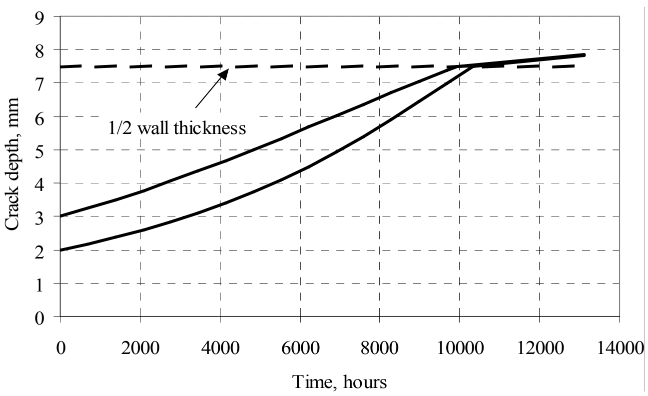

Fig. 6 Crack growth evaluation due to IGSCC mechanism in the SH-PH piping

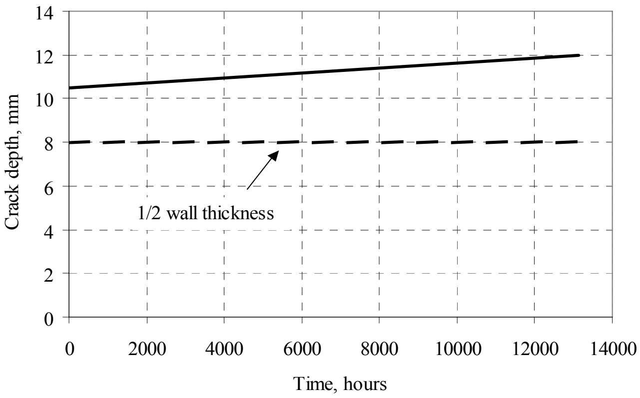

Fig. 7 Crack growth evaluation due to IGSCC mechanism in DC

Crack growth due to IGSCC mechanism for detected defect in the DC is shown in Fig. 7. Detected defect depth was 10.5 mm which is deeper than ½ pipe wall thickness. This means defect depths growth speed is 1 mm/year and after 1.5 years the defect depth will reach 12 mm.

Evaluation of defects after 1.5 years of operation is presented in FigS. 8-9. Evaluated cracks are presented by black point in this figure.

Evaluation of the defects showed that all 126 detected defects and defects after 1.5 year of operation are in acceptable region. That means that all welds in MCC can be left without repairing.

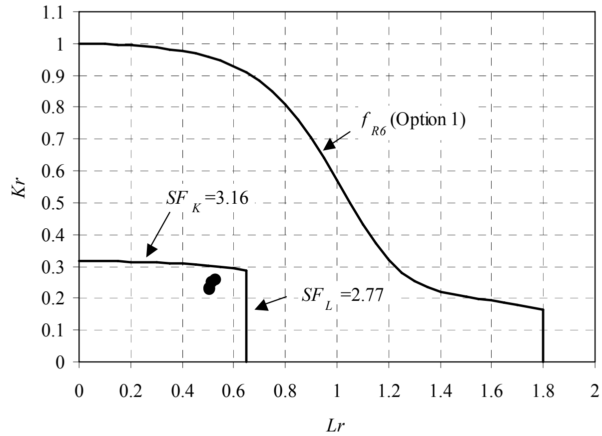

Fig. 8 Evaluation diagram for cracks after 1.5 years operation in the SH-PH piping

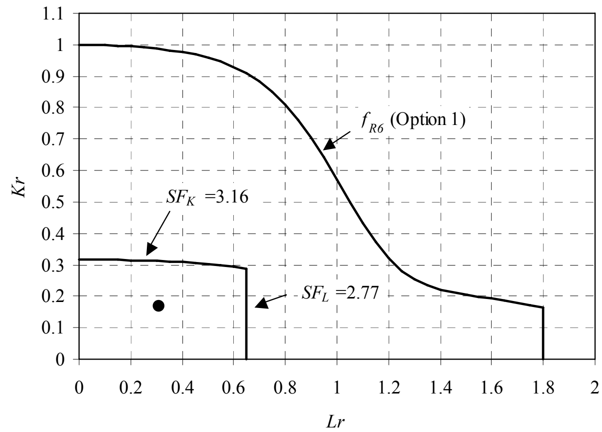

Fig. 9 Evaluation diagram for cracks after 1.5 years operation in DC

4. Summary and conclusions

The methodology of the evaluation of defects in stainless steel piping is presented in this paper. The evaluation of the defects in MCC of Ignalina NPP was performed using this methodology. The evaluation of the IGSCC defects was done using R6 method option 1. The computer code SACC 4.0 was used for this evaluation. The crack growth caused by IGSCC mechanism was evaluated according to Lithuanian regulatory requirements [6].

The analysis of the IGSCC defects in main circulation circuit in Ignalina NPP detected during planned preventive maintenance in August-September 2008 were performed and results of the most dangerous defects were presented in this article. The analysis showed that estimated IGSCC defects are in acceptable region. The growth rate of the IGSCC defects has been taken in account and showed that these defects will be acceptable after 1.5 years (13125 hours) operation.

Acknowledgments

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NERŪDIJANČIOJO PLIENO VAMZDYNŲ DEFEKTŲ ANALIZĖ

R e z i u m ė

Straipsnyje pateikiamas Ignalinos AE 2-ojo bloko pagrindinio cirkuliacinio kontūro vamzdynuose 2008 metų planinio remonto metu aptiktų defektų įvertinimas. Defektų įvertinimo procedūra susideda iš dviejų dalių: defekto priimtinumo įvertinimo bei defekto didėjimo skaičiavimo. Šiems skaičiavimams buvo taikomas R6 1-osios parinkties metodas. Analizė parodė, kad visi 126 defektai, aptikti planinio remonto metu, yra priimtino didumo, o visas vamzdynas gali būti eksploatuojamas suvirinimo siūlių neremontuojant.

Net ir sustabdžius atominę elektrinę šie vamzdynai bus naudojami dezaktyvacijai reaktoriaus išardymo metu. Todėl šių vamzdynų hermetiškumas turi būti užtikrinamas ir reaktorių sustabdžius, iki bus atlikta vamzdynų dezaktyvacija. Remiantis šiame straipsnyje aprašyta metodika turės būti atliekamas vamzdyno defektų įvertinimas.

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ANALYSIS OF DEFECTS IN STAINLESS STEEL PIPING

S u m m a r y

This article presents the evaluation of defects detected in the austenitic stainless steel piping in the main circulation circuit of Ignalina NPP Uunit 2 during the last planned preventive maintenance in 2008. Defect evaluation procedure consists of two parts: the evaluation of defects acceptability and the second part consists of crack growth calculation. For the evaluation of defects R6 option 1 method was used. The analysis showed that all 126 detected defects during planned preventive maintenance in 2008 are in acceptable region and all the welds can be used without repairing.

These piping will be used even at NPP decommission stage during decontamination procedure. Therefore the impermeability of piping should be ensured for decommissioned NPP until decontamination of the piping will be done. Evaluation of the defects in austenitic stainless steel piping should be done according to the methodology described in this article.

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