Evaluation of metal ageing of Reactor Pressure Vessels in a Nuclear Power Plant under the influence of ageing mechanisms and environmental conditions

Galya Dimova

Abstract The reactor metal in NPP is subjected to ageing mechanisms – corrosion, erosion, fatigue and neutron fluence embrittlement. These mechanisms cause degradation of the mechanical properties and may lead to the occurrence of defects. Environmental conditions are high pressure and fluid temperature values along the primary circuit. Where defects occur, it is possible to observe fracture of the metal under the environmental conditions. The RPV metal was studied by non-destructive testing methods. The article contains the results of the methods applied. In the defects site the values of fluence, circular stresses and temperatures were defined for a reactor operating under accident conditions. The impact of these factors in creating zones in the metal with risk of destruction has been considered. The results show, that corrosion and erosion have not caused defects in the metal. Neutron fluence and its thermal impact on the metal have caused embrittlement which is manifested by indications of defects. Two main factors were observed that lead to the creation of sites with a potential risk of fracture: 1) the neutron and thermal embrittlement of the metal and 2) the hydraulic stresses from the fluid. The stress intensity factors of some defects, as well as the critical values of these factors have been calculated. The comparison of these values demonstrates that the metal in the danger zones will not be damaged.

Key words: NPP ageing, Reactor Pressure Vessels, ageing mechanisms, stress intensity factor**,** environmental conditions.

Introduction The reactor metal in NPP is subjected to ageing mechanisms. The degradation mechanisms of WWER type of reactors are known – corrosion, erosion, fatigue and neutron fluence embrittlement [1, 2]. However, the influence of these mechanisms varies from one NPP to another and depends on many factors: the values of the loads in force, the preventive measures for testing and maintenance, the monitoring of the metal and the equipment, the composition of the fluid, the provision of spare parts, the safety culture. Procedures have been developed to study the ageing effects of NPP equipment [2÷6]. These procedures are strictly followed when activities are carried out to extend the NPP lifetime. In practice, under the conditions of an operating unit, it is necessary to evaluate the ageing effects through their complex impact and in conjunction with the current environmental loads [5, 7÷9]. In the event that the RPV metal has become brittle after many years of operation, it is expected to have areas with a potential risk of destruction. An NPP must operate safely and therefore areas with potential demolition risk shall be investigated. To ensure the safety of a nuclear power plant, the behaviour of the embrittled metal under the influence of the surrounding operating conditions should be investigated. According to the NPP technology specification, such assessments shall be made after each annual outage [10÷12]. Objects of study are the metal of welded joints of the reactor vessels. The condition of the metal is examined by methods of non-destructive testing – visual testing (VT) and ultrasonic testing (UT). These methods (standardized) form part of the maintenance and repair activities of an operating NPP. The survey period covers 30 years. Defects in the metal are expected to be found. Non-destructive methods can determine the parameters of the defects and their location in the RPV wall. The active loads are traced at the defect's sites, e.g. determining the values of neutron fluence, pressure and temperature of the fluid. Normative strength criteria are applied to assess the RPV operability. The presented approach for the evaluation of the effects of ageing in environmental conditions is important in conducting technical diagnostics of NPP facilities, to prepare probabilistic analyses, to extend the service life of the unit.

Materials and Methods The subject of assessment was the reactor pressure vessel (RPV) metal and the RPV of WWER 1000 – B 320 reactor type, with thermal power of 3000 MW. The materials include: 1) base metal (ferrite-pearlite steels and austenitic steel float) and 2) weld metal (austenitic steel). Two power units were the subject of survey: unit "a" and unit "b". The survey period covers 30 years. The operating environment conditions are: 1) large number of the strength cycles, 2) fluid pressure of 17.8 MPa, 3) fluid temperature 20 ÷ 330 ^{o}C, 4) fluid flows at high speed. The RPV metal is subject to the degradation mechanisms [1, 7, 12, 13]. The mechanisms and the large number of the strength cycles can cause defect(s) in the metal structure. Methods for the detection and measurement of defects are non-destructive methods – visual and ultrasonic methods [13]. Non-destructive examination methods enable finding discontinuities (defects, cracks) and studying their parameters, i.e. location, type, size, orientation. The visual testing method enables detecting and diagnosing surface discontinuities on the RPV inner surface. The RPV metal, both on the inside and on the outside surfaces can be tested through scanning using a remote system for visual inspection. The controlled parameters are: presence or absence of discontinuities, their type, size and location [10]. To examine metal, a remotely operated visual inspection system is implemented. A special software serves for storing data on the location of defect indications, sizing and comparing with previous data. The ultrasonic method of testing is applying ultrasonic scanning type of equipment permitting sequential sounding of all parts of the reactor pressure vessel (object of control). The sounding means a signal is input in the metal and then the reflected signal is registered. The UT system is remotely operated. Software instrumentation is employed to register the results. All identified images for defect indications are stored in the memory, their size taken, as well as their coordinates. To complete this activity a UT system, type P-scan, for the RPV inner surface is used together with a Tomoscan type of system. The expectations are to find defect(s) in the metal, if such are present in the RPV metal. The measured parameters of the potential defects are locations (coordinates) in the metal, sizes and orientation in the RPV inner surface. If indications of defects have been found, their parameters get identified, i.e., length, location and size of equivalent area (UT characteristics of the indications). A data base is established and the defects' data are input in it. A screening of the defects is performed for the purpose of further assessments and calculations. Evaluations are conducted on the impact of the environmental conditions. The location is an important factor as the values of the fluence and the thermohydraulic loads tend to change in the different points of the RPV. Knowing the location of the defect, we are looking to determine what the acting loads are at this place in the reactor wall. A neutron fluence distribution in the wall is taken from measurements performed by back-hull fluence detectors. Data of the neutron fluence are collected on an annual basis by monitoring the readings of the neutron detectors (reactor in-core detectors). As regards the fixed locations of the indications (critical zones), the circular stresses and temperatures are considered under the different operating modes of the reactor unit. Several of the "most risky" discontinuities are selected and calculations are made about them. Selection of defects means the parameters of all the identified discontinuities are reviewed. For each discontinuity selected, calculations are made to obtain: 1) the current values of the stress intensity factor K_I, and 2) the critical values of the stress intensity factor $[K_I]$. Brittle fracture toughness is ensured if the current values of the stress intensity factor K_I is less than the critical one with regard to the discontinuity found [15]. Calculations are made of the stress intensity factors K_I for selected indications. The calculations were carried out according to the strength rates [15]:

$$K_I = Y.\sigma_k.\sqrt{a} \qquad (1)$$

Where σ stands for the load, and Y is a coefficient related to the discontinuity shape, a is the small semi-axis of the discontinuity. The values of the stresses and temperatures were taken from the strength analyses of the equipment manufacturer. To ensure conservatism of the calculations, the highest values are used for: 1) circular stresses, 2) temperatures under all the design modes.

Calculations are made for the critical values of the stress intensity factors $[K_I]$. The calculations were carried out according to the strength rates [15].

The results obtained for the stresses intensity factors K_I are compared with the critical ones $[K_I]$.

$$K_I \leq [K_I] \qquad (2)$$

In case condition (2) is not met, strength analyses are required. The algorithm for evaluating the brittle burst hazard is shown in Fig.1.

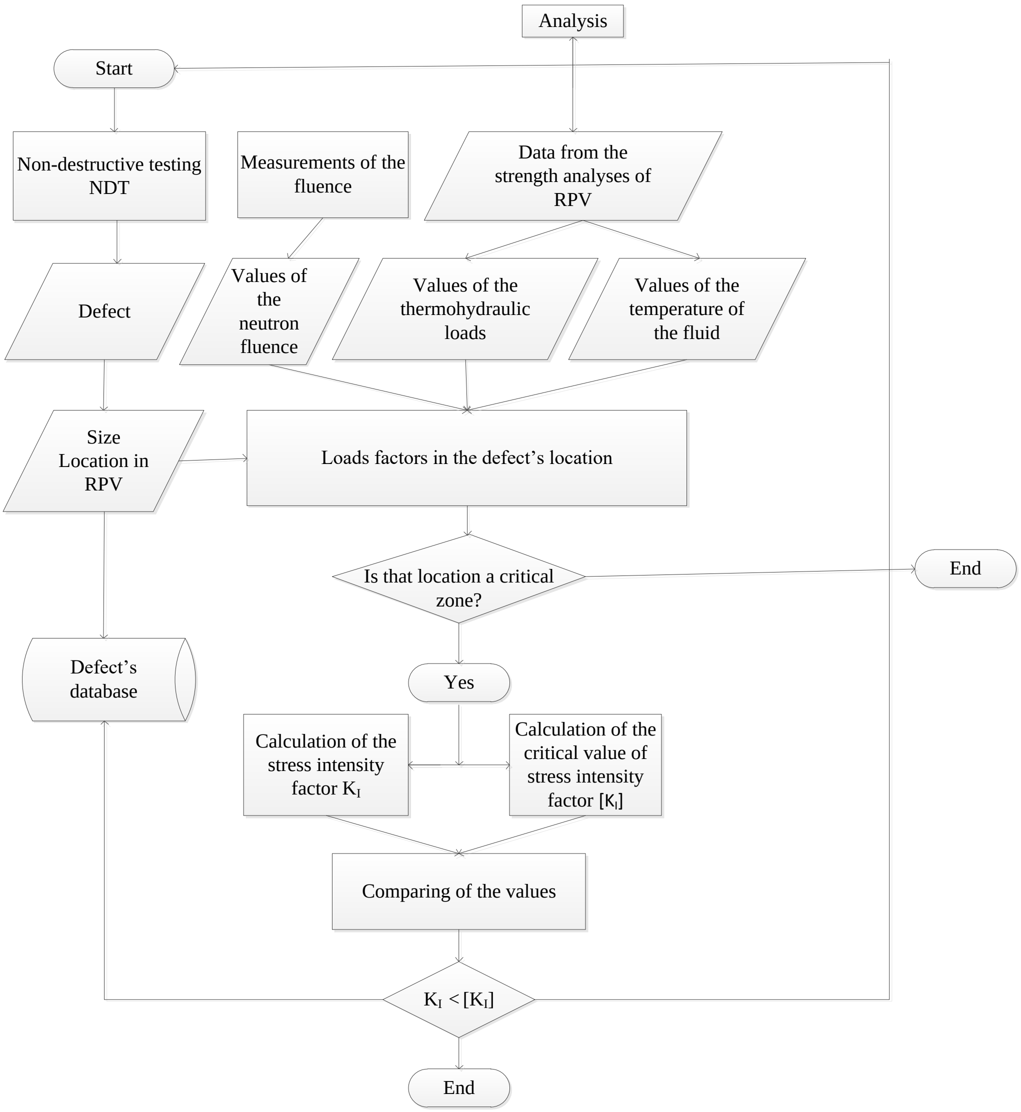

Fig. 1. The algorithm for evaluating the brittle fracture, based on the metal resistance to the defect's growth.

Results Non-destructive visual testing and ultrasonic testing were performed. The indications parameters, such as size, location coordinates, year of size taking, were assessed. The data of a welded joint indications and the relative values of the neutron fluence F/F_{max} are shown in Table 1.

Table 1. Indications of welded joint “X” of the reactor pressure vessel – sizes, coordinates and neutron flux at the site of the indications.

	Welded joint “X”, indications - size and coordinates: a) Along the weld; b) Along the reactor height; c) In depth of the weld, on the outside.					
Indication No.						
Size [mm]	478	39	39	150	55	27
a) [grad]	64.4	79.9	85.4	88.4	104.9	107.4
b) [mm]	274.5	276.3	277	276.7	276.8	277
c) [mm]	520	52	53.7	51.4	51.6	50.6
Neutron flux F/F_{max}	0.15	0.15	0.15	0.15	0.15	0.15

The typical transitional state of “accident conditions - primary circuit large leak” has been considered. Pursuant to the register of the implemented operational cycles, the large leak mode is associated with the highest amplitude values for stress-temperature fields. The values of the circular stresses and the temperature at the locations of discontinuities are provided in Table 2.

Table 2. Stresses values σ - circular stresses of the base metal inner surface at the locations of discontinuities.

Weld joint/ Indication No.	Values of circular stresses σ [MPa] / temperatures [°C] at the locations of discontinuities for the “primary circuit large leak” mode		
	0,2 hours	0.4 hours	0.6 hours
X / I	210 / 260	170 / 180	160 / 158
X / II	210 / 260	170 / 180	160 / 158
X / III	210 / 260	170 / 180	160 / 158
X / IV	210 / 260	170 / 180	160 / 158
X / V	200 / 260	175 / 178	160 / 150
X / VI	240 / 250	190 / 190	180 / 160
Y / I	487 / 70	350 / 55	260 / 45
Y / II	80 / 240	175 / 177	150 / 145
Y / III	110 / 210	10 / 160	35 / 130
Y / IV	250 / 250	190 / 190	185 / 167
Z / I	450 / 150	140 / 110	130 / 70
Z / II	210 / 108	250 / 65	200 / 60
Z / III	200 / 240	115 / 170	120 / 140

The stress intensity factors K_I were calculated for selected indications. The results for the calculations of K_I are provided in Table 3.

Table 3. The results for the calculations of the stress intensity factors K_I under accident condition, primary circuit large leak mode.

Weld joint/ Indication No.	$\mathbf{K_I}$, circular stress, under emergency condition, primary circuit large leak mode, [MPA.$\sqrt{\mathbf{m}}$]		
	0.2 hours	0.4 hours	0.6 hours
X / I	21.02	17.02	16.02
X / IV	23.8	19.2	18.1
Y / I	60.21	43.27	32.14

Calculations were made of the limit values of the stress intensity factors $[K_I]$ under accident condition, primary circuit large leak mode. The results about indication No.1 of weld joint "Y" is: $[K_I] = 108\ Mpa.\sqrt{m}$.

Discussion The results of the visual test carried out showed no surface defects observed in the metal at the inner surface of the reactor. Since the visual method can detect surface defects, this demonstrates that metal is not damaged due to corrosion, erosion or wear. The ultrasonic test found indications of defects in the RPV metal inner surface. Defects are observed both in zones with large fluence (welds "Y", "Z") and zones with less fluence (weld “X”). This means that metal degradation is present due to fatigue, neutron and thermal embrittlement. Large size defects present particular danger. Their location is tracked in terms of the distance from the RPV inner surface. The UT indications having the largest area and location close to the inner surface of the RPV are considered to be subject to the comprehensive impact of the environmental conditions inside the pressure vessel, i.e., high values for the neutron fluence and thermohydraulic loads. An assessment is made to decide which of the indications are located in zones with a degradation potential. The orientation of the defects is of great significance with regard to the direction of the active loads.

Estimates show the UT indications that contain a risk of disruption are two: 1) of welded joint “X”, indication No. I and 2) of welded joint “Y”, indication No. I. The data for these are shown in grey in Tables 1÷3. Let's take a detailed look at the two indications. Indication No.I of welded joint “X” is relatively long and is sited close to the inner RPV surface, but the neutron fluence value is the same as for the other indications of welded joint “X”, (Table 1). At the location of Indication No.I of welded joint "X", the values of the circular stresses and temperatures of the "primary circuit large leak" mode are high (Table 2), and it is, therefore, appropriate to calculate the stress intensity factors $\mathrm{K_I}$ (Table 3). We will now look at the data for indication No.I of welded joint “Y”. Welded joint “Y” is located opposite the RPV core. Circular stresses at the location have very high values for the “primary circuit large leak” mode. The operating temperatures in this location have relatively low values (Table 2). The defect is located perpendicular to the existing tensions - the most dangerous case.

The stress intensity factor K_I has the greatest value compared to the other indications, 60,21 MPA.$\sqrt{m}$ after 0.2 hours for the “primary circuit large leak” mode (Table 3). The results show that the most dangerous case of defect is that of welded joint “Y”, indication No.I. For Indication No.I of welded joint “Y” a comparison was made between the current values of the stress factor K_I and the limit value $[K_I]$:

$$K_I=\{60{,}21;\ 43{,}27;\ 32{,}14\}\ \text{MPA}.\sqrt{m} < [K_I] = 108\ \text{MPA}.\sqrt{m} \qquad (3)$$

For UT indication No.I of welded joint "Y", which is the most serious case of defect, for the “primary circuit large leak” mode, the condition of strength norms for resistance to brittle fracture is fulfilled. It is not necessary to conduct strength analysis at this stage. In effect, this means that the RPV can operate safely.

The proposed algorithm can serve to evaluate the ageing effects on the RPV metal. It can be used in the preparation of RPV probabilistic assessments, in the development of strength analyses, in case of unit lifetime extension.

Conclusions

The reactor vessel metal is subject to degradation mechanisms. Corrosion and erosion have not caused defects in the metal. Neutron fluence and its thermal impact on the metal cause embrittlement which is manifested by indications of defects. But it cannot be argued that fluence alone is the cause of the defects. Two main factors are observed that lead to the occurrence of sites with a potential risk of fracture: 1) the neutron and thermal embrittlement of the metal and 2) the hydraulic stresses caused by the fluid. In areas where there are already defects, the stresses due to the environmental conditions act as the factor of the greatest impact.

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Assistant Galya Dimova
Technical University of Sofia, Technical College - Sofia
Department of Energy and Mechanical Engineering
Sofia, bul. “St Kl. Ohridski” 8, Studentski complex
Tel. +359 888 578 129, dimova@tu-sofia.bg, gtdimova@abv.bg