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Reactor Pressure Vessel Internals – research on the effects of aging caused by operating conditions

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Abstract

The operating conditions of a nuclear reactor vessel are characterized by high values of pressure and temperature of the fluid along the primary circuit, variable loads, intense neutron fluxes and a corrosively aggressive environment. All this factors causes aging of the Reactor Pressure Vessel (RPV) Internals metal. The mechanisms of degradation of the mechanical properties are neutron and thermal brittleness, corrosion, erosion, fatigue and wear. Corrosion of the metal is caused by the fluid along the primary circuit of the nuclear power plant. The high values of the reactor temperatures and the operating stresses cause stress corrosion and corrosion fatigue. Neutron flux causes the most damaging effect on the metal structure. After prolonged periods of exposure to high-energy neutrons (several decades), the metal of the reactor vessel becomes brittle and strengthened. Temperature and dose load gradients can cause swelling of the metal of the reactor internals. Swelling is an increase in the external dimension of solid materials after irradiation and is an extremely dangerous condition of the metal structure, because it reduces the bearing capacity of structures. In addition, the change in the geometric dimensions of the RPV Internals may disturb the movement of the heat carrier and the heat balance, to obtain jamming and blocking of units of the reactor control and protection system. This article discuss the reasons for the degradation of the mechanical properties of RPV Internals. Two methods for studying the effects of aging on objects are presented – visual method for monitoring the condition of the metal and method for measuring geometric dimensions, as well as the results obtained.

Keywords

Nuclear reactor, Internals, corrosion, swelling

1. Introduction

The policy of each Nuclear Power Plant (NPP) is to ensure safe production of electrical energy as well as security of supply. The operating temperatures in the primary circulation circuit are 270÷320 ^{0}C, the pressure reaches 17,5 MPa. The metal of NPP equipment is affected by aging mechanisms formed by the working environment –

neutron and thermal brittleness, corrosion, erosion, fatigue and wear [1]. These influencing factors change the mechanical properties of the metal and reduce the bearing capacity of the structures. After several decades of operation of the nuclear unit, it is usually necessary to prepare (or revalidate) strength analyses of the equipment to ensure its safe operation [1,2]. Corrosion of the metal is caused by the working medium – water with various reagents added (primary circuit fluid). The high values of the reactor temperatures and the operating stresses cause stress corrosion and corrosion fatigue. The radiation environment causes general and intergranular corrosion. Corrosion damage is complemented by the processes of erosive washing away from the flowing fluid. On the other hand, high fluence values ($1{,}5.\,10^{22}$ neutrons$/m^2$per year) from neutrons with an energy greater than 1 MeV can cause changes in the structure of the irradiated material. **Figure 1** shows nanostructured images of irradiated materials [3]. Cluster formations of atoms of the chemical elements copper Cu, phosphorus P and silicon Si are observed.

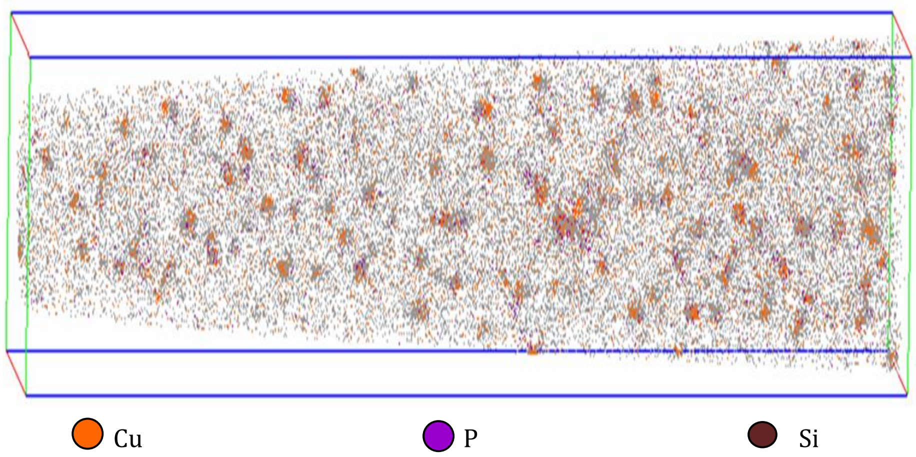

Figure 1 A. Welded joint EW-P2 R7-00561 with a high content of Cu, Irradiated with high fluence, sample sizes 30x29x232 nm^3.

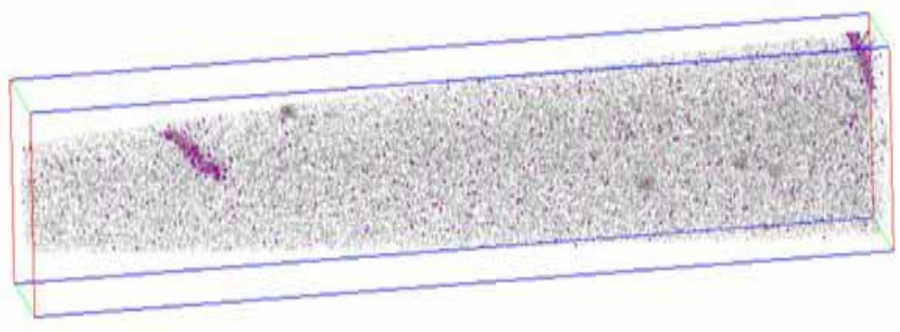

Figure 1 B. Low Carbon Steel Cu- 0.03Cu, 6x10^{19}n/cm^2.

The uneven metal structure is the root cause of the brittleness of RPV Internals metals. (In the state of brittle fracture, metal fracture can occur suddenly and unpredictably, with a small influx of external energy). The neutron flux produced by the chain reaction of the decay of uranium fuel in the core causes the neutron and thermal brittleness of the metal [4]. The essence of the problem is: 1) Swelling is an increase in the external dimension of solid materials after irradiation. 2) Vacations created by the materials that make up the inside of the reactor as a result of irradiation can accumulate in cavities, which can lead to changes in the dimensions of the material. 3) A change in the dimensions of the Internals leads to a decrease in the distance, a violation of the movement of the coolant and the heat balance, and may lead to jamming and blocking of control and protection system units. Swelling is an increase in the external dimension of solid materials after irradiation and is an extremely dangerous condition of the metal structure, because it reduces the bearing capacity of structures. **Figure 2** shows diagrams of Reactor Pressure Vessel Internals and Core Barrel.

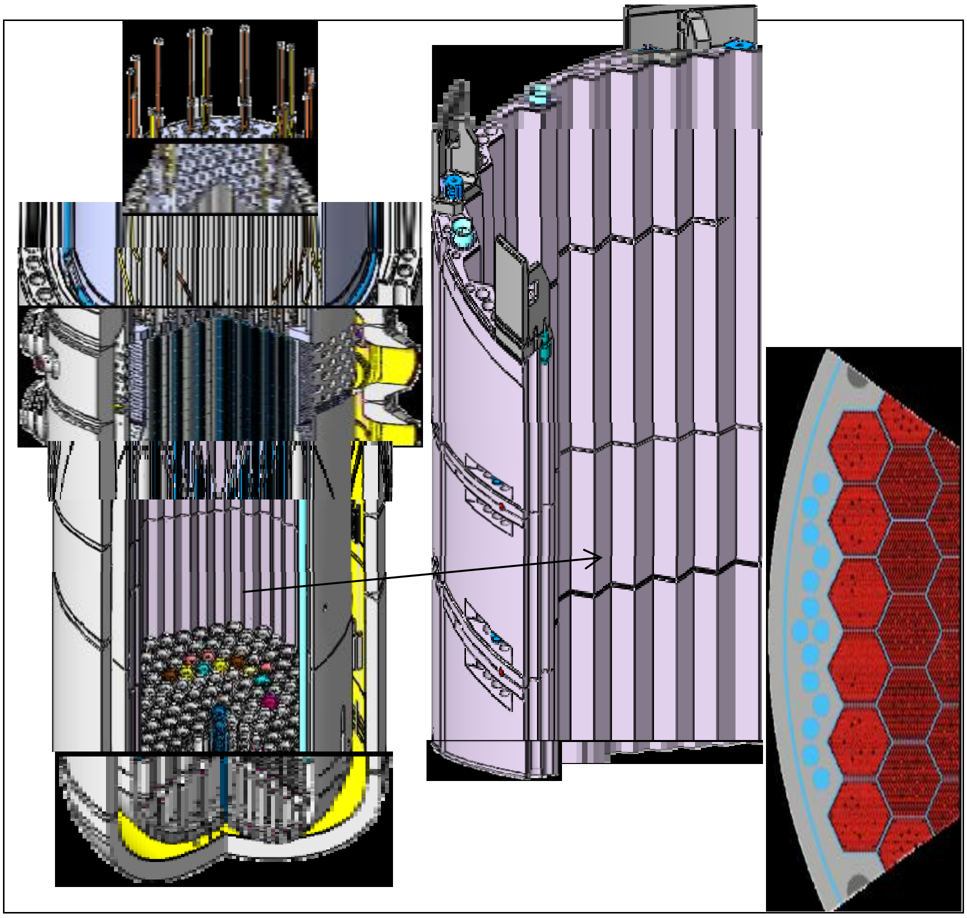

Figure 2. Reactor Pressure Vessel Internals (Left) and Core Barrel (Right).

The Core Baffle is important to safety because it provides a high concentration of the reactor coolant flow in the core region. The Core Baffle is made up of vertical plates called baffles and horizontal support plates called formers. The baffle plates are bolted to the formers by the baffle/former bolts, and the formers are attached to the core barrel by the barrel/former bolts. The Baffles provide a barrier between the core and the former region so that a high concentration of flow in the core region can be maintained [5]. The geometry of the Core barrel is the same as that of the core - it is a shell structure. The change in the size of the Core Baffle would cause a reduction in the distance between the Core barrel and the fuel assemblies, violation of the movement of the coolant and the heat balance; may lead to jamming and blocking of the control roads and protection system. In some operating modes, it is possible in the event of an ECCS incident (Emergency Core Cooling System) to realize fast cooling (Pressurized Thermal Shock). The Core barrel is the most irradiated part of the reactor, it guarantees the safety of the reactor plant. The environmental conditions of the working environment are: 1) Max rate of damaging dose in the metal; 2) The temperature varies 290-320 °C on the surface and up to 400 °C in the inner layers due to γ irradiation, [4]. All these processes of modification of mechanical properties are envisaged in the design of the plant. To ensure the safe operation of a nuclear reactor, different procedures are in force in different countries [6,7]. However, there is no requirement in the technological regulation to regularly measure the actual geometric dimensions of the internals housing devices. This article discusses the main Core baffle and the Core Barrel as an object of measurement. The metals of the objects were studied for the effect of two mechanisms of degradation of mechanical properties - general corrosion and swelling.

2. Materials and Methods

The Core Baffle materials are austenitic steels and ferrite-pearlite steels with austenitic surfacing. Austenitic steels are corrosion-resistant, have appropriate technological properties, work up to temperatures of 700°C; steels of type 08X18H10T are radiation-resistant (for VVER reactors 440). Alloyed Pearlite Chromium-Molybdenum-Vanadium Steel 15X2HMΦA (15H2NMFA) has two layers of austenitic overlay (for VVER 1000 reactors). Steels 15X2MΦA (15H2MFA), 15X2HMΦA (15H2NMFA), A542, A543, A508 have resistance to radiation brittleness, high strength and good plasticity (R_e = 500÷900 MPa), are not corrosion-resistant. The mechanisms of degradation of mechanical properties are determined, **Table 1.** The assessment is carried out on the basis of the technical condition of the facilities after more than 30 years of operation, and information from other NPPs is also taken into account.

Table 1. The mechanisms of aging of RPV Internals metal.

Equipment	Degradation of the mechanical properties	
	Critical component	Aging mechanism
Reactor Internals	Welded joints	Fatigue
Core Baffle	Base metal	Intergranular corrosion
Core Barrel		Crawling from radiation Radiation swelling Radiation brittleness Corrosion under radiation stresses

This study investigates the effects of aging induced by the mechanisms of corrosion and swelling. Corrosion is examined by a visual method of inspection by remote means [8]. The specific objects of study by visual method are from the equipment of three NPPs, type WWER, **Table 2.** The study period covers 35 years.

Table 2. RPV Internals Objects of study by visual method of inspection.

Equipment	Critical component	
	Exterior surface	Inner surface
Reactor Pressure Vessel	-	Overlay – base metal and welded joints
Core Barrel	Core barrel flange, **Figure 3** Flange pipe attachment nodes	Keyways on the top attachment of the Block Protective Pipes (BPP), **Figure 4**
	Surface of keyways for top/bottom fastening of Core Barrel	Welded key joints of the bottom/top attachment of BPP
	Base metal and welded joints, from the flow divider to its elliptical part	Base metal of the keys of the bottom attachment of BPP
	Bottom	Welded joints of the keys on the upper attachment of the Core Barrel
		Support pipes of the Core Barrel
		Perforated part and bottom of the support tube

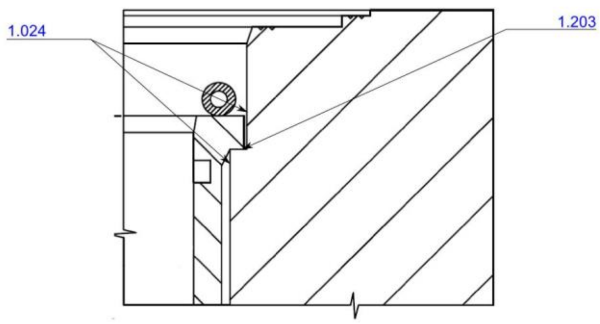

Figure 3. Core barrel flange.

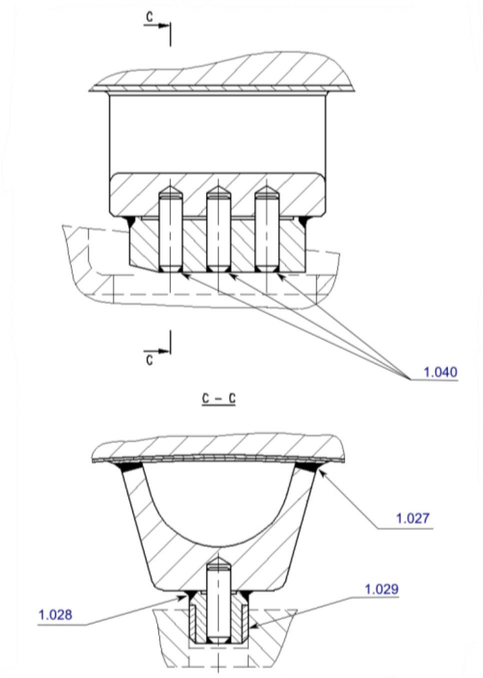

Figure 4. Core barrel fixation in RPV (key - groove and tongue).

The equipment and the visual inspection scheme are presented at **Figure 5.**

Figure 5 A. Underwater system SIMENS SUSI 420.

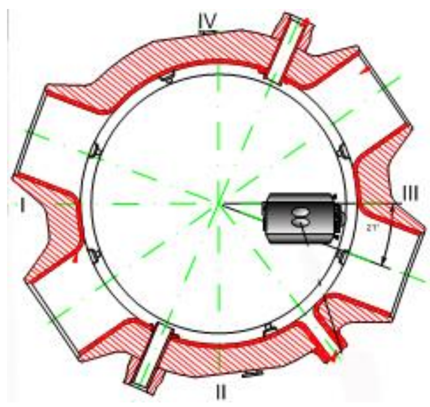

Figure 5 B. Scheme of visual inspection of the Core barrel.

The measurement of geometric dimensions of the Core barrel is carried out on the basis of the triangulation method, **Figure 6**, [9].

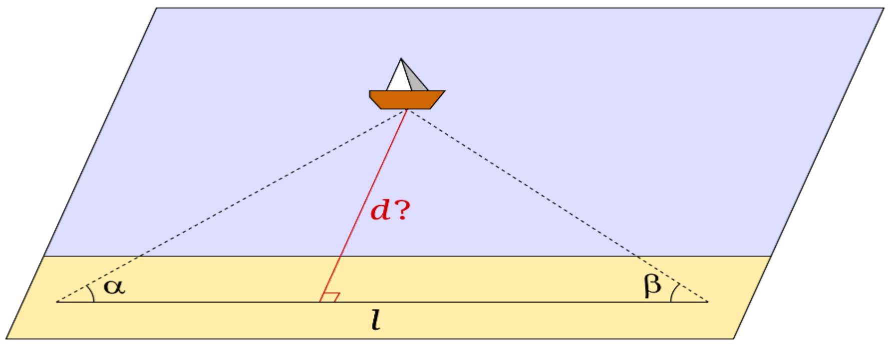

Figure 6. To find the distance from the shore to the ship, the triangulation method is used. Observers in points α and β measure the distance between them and the corners α and β. To calculate the distance d the length l is used and the corners α and β.

The known dependencies of such triangles are used. In this method, a television probe (camera) is used, which has a fixed part and a rotating part. A light source (laser) is attached to the rotating part, **Figure 7**. The laser beam scans the wall of the Core barrel step by step. Through the camera, the image of the metal is monitored and recorded. The distance from the probe to the Core barrel wall (AB) is measured. Any deviation from the initially set value of this distance (reference value) is registered.

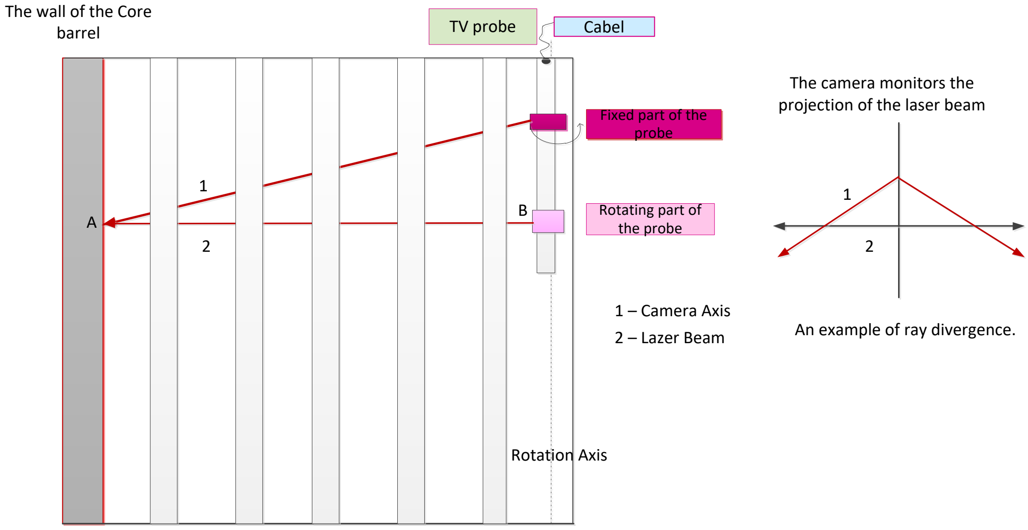

Figure 7. Scheme for measuring geometric dimensions of the Core Barrel.

This method of geometrical dimension research is applied to two WWER 1000 units. The period of operation of one unit is 32 years, and the other unit is 30 years.

3. Results

The results of a visual examination of the Core Barrel metal of three WWER blocks show that no corrosion spots are observed on the surface of the objects. Corrosion ulcers are noticeable only on the inner surface of the reactor vessel in the places of upper attachment of the elements of the Core baffle, **Figure 8.**

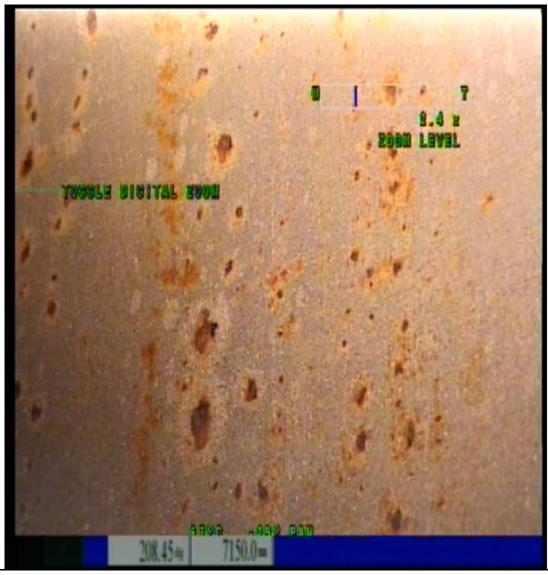

Figure 8. Corrosion and erosion foci concentrated in the zone of bulging by the reinforcing units of the internal housing devices.

Individual surface inconsistencies (defects) in the shell surfacing are observed and their parameters are determined. An analysis is being carried out whether the defects are permissible according to the regulatory requirements.

A measurement of the geometric dimensions of the Core barrel was carried out during operation. The specific indicators of the measurement carried out are:

1) Coverage of the measured distance - 1450 ÷ 1650 mm; Discrete distance value – 0,1 mm; absolute distance measurement error, ± 0,5mm;

2) Rotation Angle Measurement Range, 0 ÷ 360 ^{0}; Discrete Angle Value, 0,0001^0; Absolute Rotation Angle Measurement Error, ± 0,5^0.

The measurement results obtained are given in **Figure 9**.

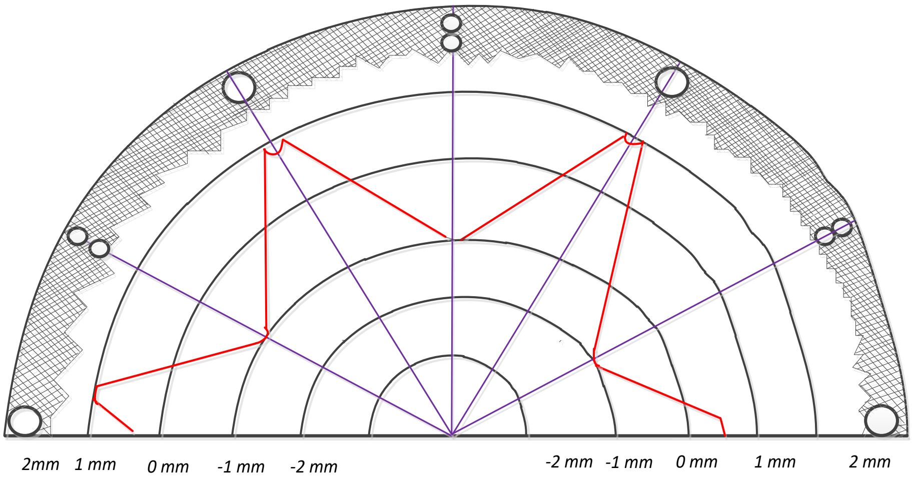

Figure 9. Results obtained from the measurement of the Core barrel (red line).

The presence of the zones with maximum displacement is shown in **Figure 10**.

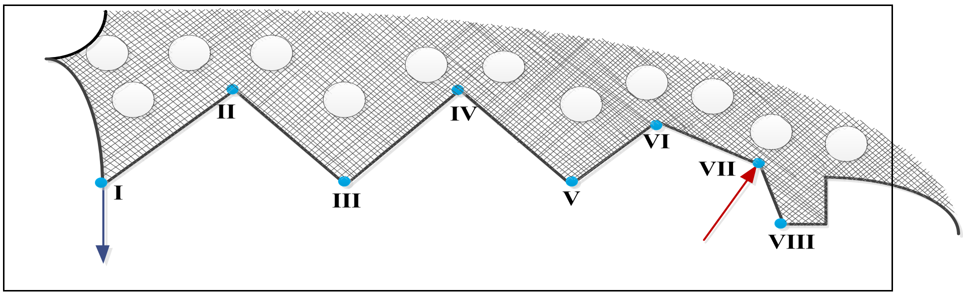

Figure 10. The areas with maximum displacement and the direction of displacement (with arrows).

Measured results by height of the Core barrel are presented in **Figure 11**.

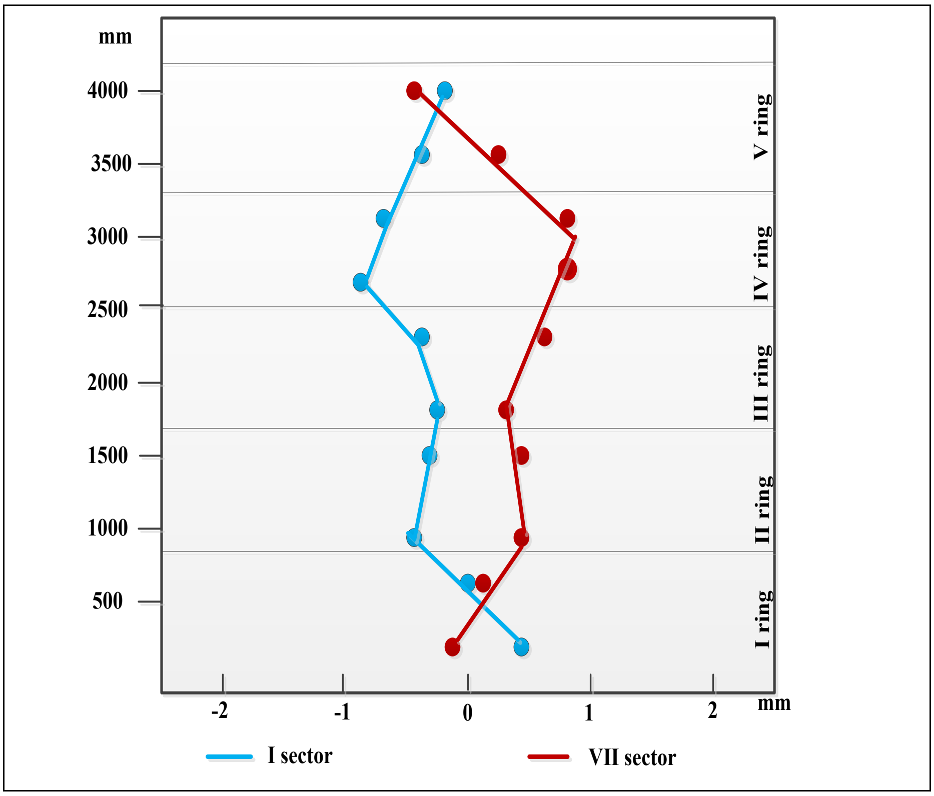

Figure 11. The sectors with maximum displacement are I and VII; the displacement dimensions are less than 1 mm.

4. Discussion

The assessment of resistance to corrosion and erosion wear (general corrosion) is made by the aging index – the type, size and location of surface defects of the metal from the inner surface of the reactor vessel. The defects found are admissible according to the regulatory documents, therefore, the requirement for resistance of the metal to corrosion and erosion wear is met.

The assessment of swelling resistance is carried out by the indicator change in dimensions. The results obtained show that there is no significant change in the geometric distances of the Core barrel, compared to the passport data. The displacement dimensions are less than 1 mm. The metal is resistant to swelling. It is assumed that until the next such measurement (after 4 years) there will be no (significant) change in the geometric distances.

5. Conclusions

The metal of the internal casing devices of the nuclear units, type WWER, is resistant to corrosion and swelling. This conclusion can be made under the very important condition that nuclear units are operated (must be operated!) in accordance with the requirements of the technological regulation. The presented method for measuring the swelling of the Core barrel metal caused by neutron and thermal effects is an easy and affordable way to regularly measure the actual geometry of the Baffle walls. It is easy to make comparisons with previous data and accordingly track the trend of geometry change. At present, there are no standards (procedures) for measuring the swelling of the Core barrel metal caused by neutron and thermal effects. The presented method would contribute to the development of similar standards (procedures).

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