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REVIEW ARTICLE

A STUDY FOR MEASURING CORE BARREL SWELLING IN NUCLEAR POWER PLANTS CAUSED BY OPERATING CONDITIONS

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ABSTRACT

The policy of each NPP is to ensure safe production of electrical energy as well as security of supply. The metal of NPP equipment is influenced of aging mechanisms from the working environment – neutron and thermal brittleness, corrosion, erosion, fatigue and wear. 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, and defects are expected to appear and develop in the structure, which further fragile the metal. Temperature and dose load gradients can cause swelling of the metal of the reactor internals. In this 'worst-case scenario', the distance between the core barrel and the fuel roads is expected to be reduced, to 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. At the same time, neither the regulatory framework nor the technological regulations of nuclear power plants require regular measurement of the actual geometric dimensions of the reactor internals. This paper presents a study for measuring the geometric dimensions of the Core baffle. The method is new and has not yet been studied in depth. The aim of the article is to present a possible way to measure the geometric dimensions of the Core barrel due to expected swelling of the metal due to neutron and thermal effects. The mechanisms of degradation of mechanical properties of the metal are presented. From a practical point of view, this information can be used to carry out technical diagnostics of the equipment in NPPs.

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INTRODUCTION

The policy of each 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 [https://www.iaea.org/ publications/ 13475/ageing-management-for-nuclear- power-plants-international- generic-ageing-lessons-learned-igal]. 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 [https://www.iaea.org/publications/13475/ageing-management-for-nuclear-power-plants-international-generic-ageing-lessons-learned-igal; https://inis.iaea.org/search/ search.aspx?orig_q=RN:43130377].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. Neutrons have a small mass and high energy values, they can penetrate deep into the crystalline metal lattice of the reactor and internals [https:// knizhen-pazar.net/products/books/3859165-puknatoustoychivost-na-metalite-pri-statichno-natovarvane]. Neutrons easily "knock" atoms out of their equilibrium positions – this is how vacations are created. Vacations are point defects and lead to the weakening of interatomic bonds. Vacations (Fig. 1 A) migrate into the metal structure, can accumulate in cavities in the metal, which in turn can lead to changes in the dimensions (swelling) of the material. Atoms from the surface boundary between individual grains or blocks in grains also represent defects. This type of defect is the mosaic structure. Each grain consists of separate defect-free blocks, or sub grains with dimensions of the order of $10^{-6} \div 10^{-8}$m, which conclude smaller angles (small-angular borders). The sub grains at the borders represent (perceived as) surface defects (the red zone in Fig. 1 B). It is here that vacations, knocked out atoms, impurity atoms (phosphorus and sulphur) accumulate. In these places, weak interaction bonds are created between the building blocks. Therefore, the space between the crystal grains in the metal structure is susceptible to intergranular corrosion. In short, neutrons cause point, surface and bulk defects in metals. Neutron and thermal effects cause changes in the mechanical properties of metals, Fig. 2A.

The values of tensile strength σ_B and yield strength σ_S are increased. In cases of prolonged exposure to neutron fluence (more than 2 decades), the value of the yield limit σ_S can be increased up to three times and practically approach the strength limit σ_B, Fig. 2B. The convergence of these two boundaries means that in the load-resistance diagram (the "Ϭ-ε" diagram) the drag site is "lost"; the metal loses its tough-plastic structure and reaches states of ultimate strength even at small deformation values. Brittleness and simultaneous hardening occur. There is a high risk of brittle destruction. (In the state of brittle fracture, metal fracture can occur suddenly and unpredictably, with a small influx of external energy).

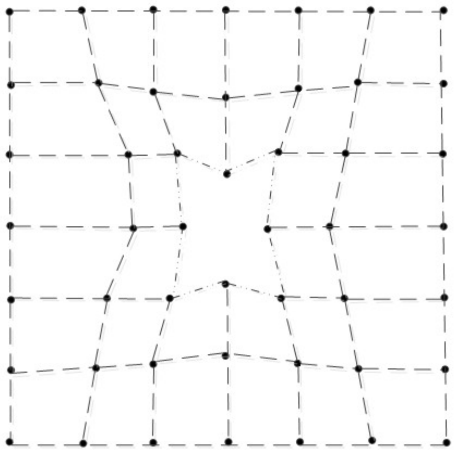

Fig. 1A. Scheme of vacation in the crystal metal lattice

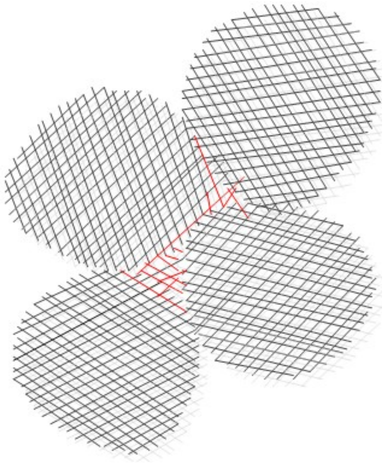

Fig. 1B. Scheme of a mosaic structure in real metal

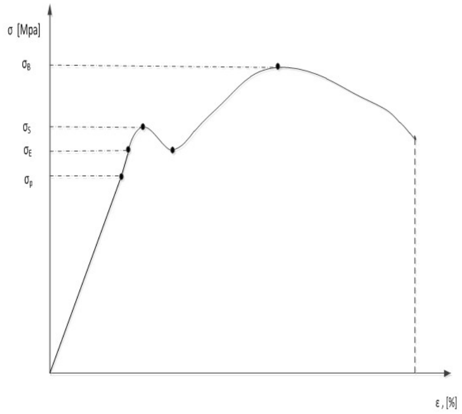

Fig. 2A. Load-resistance diagram (diagram "Ϭ-ε") of a metal, without neutron and thermal irradiation, σ_p - limit of proportionality; σ_e - limit of elasticity; σ_s - limit of yield; σ_v – tensile strength; ε – deformation value

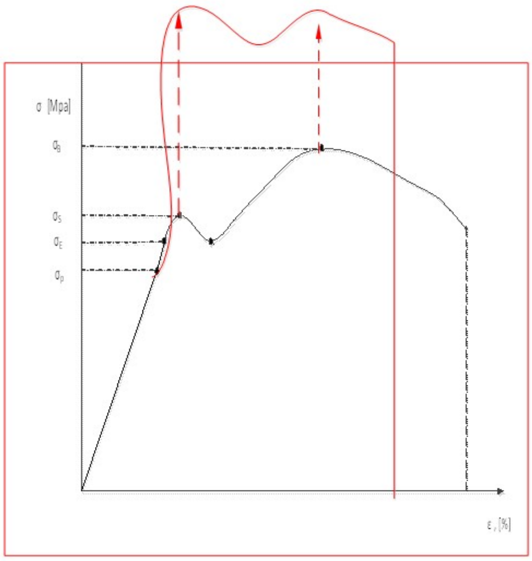

Fig. 2B. Load-resistance diagram (Ϭ-ε diagram) of a metal that has undergone neutron and thermal irradiation, σ_p - limit of proportionality; σ_e - limit of elasticity; σ_s - yield limit; σ_v – tensile strength; ε –deformation value

In addition to brittleness and hardening, as a result of neutron irradiation and the accumulation of a "knocked out phase" at the boundaries of the grains, it is expected that the geometric dimensions of the metal will be increased. 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. This article discusses the Core baffle and the Core Barrel as an object of measurement, Fig. 3A. 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 Core Baffle forms the interface between the core and the Core barrel. 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 [https://www-pub.iaea.org/mtcd/publications/pdf/te_1119_prn.pdf]. The geometry of the Core barrel is the same as that of the core - it is a shell structure. The degradation mechanisms characteristic of the Core Baffle are: radiation creep, radiation swelling, radiation brittleness, corrosion under radiation stresses. 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. These conditions create tensions (loads), Fig.3B:1) Stresses caused by the temperature gradient and radiation swelling; 2) Stresses caused by dynamic loads in design accidents; 3) Swelling and creep lead to changes in the geometric dimensions of core internals; 4) The corrosive effect of the fluid.

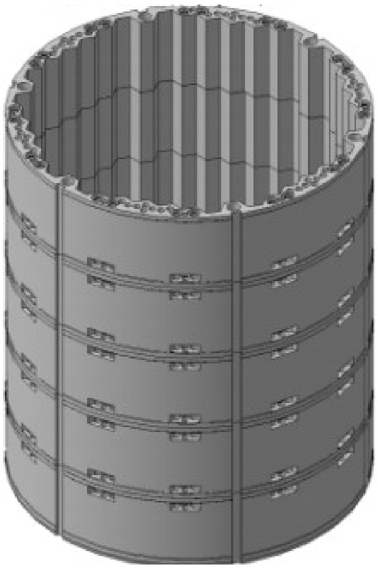

Fig. 3 A. Core Baffle

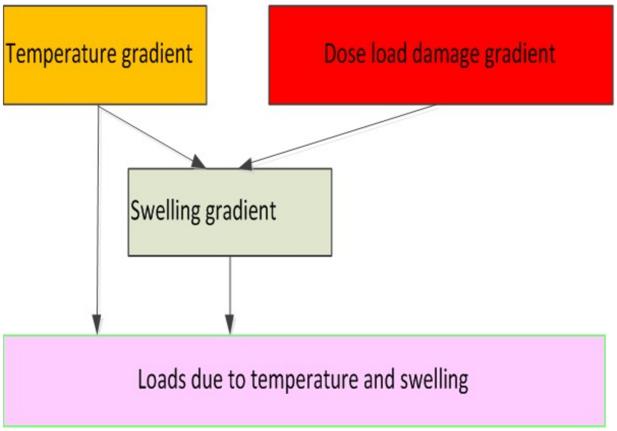

Fig. 3 B. The Core Baffle Metal Stresses Created by Operating Conditions

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 standards are in force in different countries [https://www.asme.org/codes-standards/find-codes-standards/bpvc-section-iii-subsection-nca-general-requirements-div-1-div-2/2023/print-book; https://inis.iaea.org/collection/NCLCollectionStore/_Public/30/013/30013700.pdf]. However, there is no requirement in the technological regulation to regularly measure the actual geometric dimensions of the internals housing devices. In the last ten years, experiments have been carried out to conduct measurements of the swelling.

$$S_0 = c_D . D^n . \exp\left[-r . (T_{Irr} - \mathrm{T}_{max})^2\right] \qquad (1)$$

S_0 - Swelling of the metal caused by temperature

D – dose; T_{irr} - Irradiation temperature; T_{max}= 470 ^{0}C - Maximum Swelling temperature.

$c_D = 1{,}035.10^{-4}$ сна^{-n} to describe the median dependence for swelling; $c_D = 2{,}588.10^{-4}$ $\text{сна}^{-п}$ to describe the upper limit of the swelling dependence at a confidence probability interval 0,95; n=1,88; r=0,00018 $^0\mathrm{C}^{-2}$.

Swelling S [%] taking into account the stress state of the material:

$$S = S_0.(1+P.\sigma_{eff.}) \qquad (2)$$

$\sigma_{eff.}$ – effective stresses; P – Constant on Material.

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).Steels15X2MΦA (15H2MFA), 15X2HMΦA (15H2NMFA), A542, A543, A508 have resistance to radiation brittleness, high strength and good plasticity (R_e = 500÷900MPa), are not corrosion-resistant [https://docs.secnrs.ru/documents/pnaes/%D0%9F%D0%9D%D0%90%D0%AD_%D0%93-7-002-86/%D0%9F%D0%9D%D0%90% D0%AD-%D0%93-002-86e. htm; https://www.sciencedirect.com/ science/ article/ abs/pii/ S0022311513004169]. To measure the swelling of the Core barrel, the triangulation method was applied. Triangulation is a method in elementary geometry of triangles for determining the distance to objects. In this method, the distance to a point is calculated by measuring the distance between two reference points and the angle between the object and the line formed by these points. 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, Fig. 4. 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.

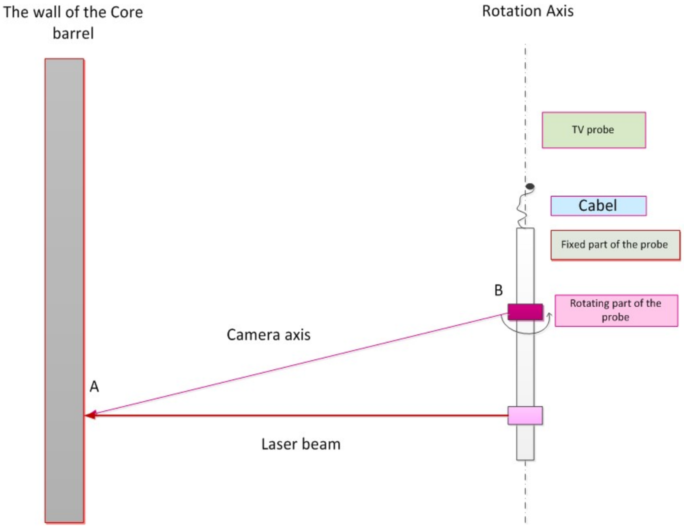

Fig. 4. Scheme for measuring geometric dimensions of the Core barrel wall

The measurement carried out has two main tasks: 1) To measure the actual geometry of the Core barrel during operation; 2) To determine the estimated geometry change by the next operational period or by the end of the reactor operation. Results A measurement of the geometric dimensions of the Core barrel was carried out during operation.

RESULTS

A measurement of the geometric dimensions of the Core barrel was carried out during operation. This measurement was carried out for two units, type VVER 1000 (conventionally called Block A and Block B), in two different nuclear power plants. The years of operation of Unit A are 30, and Unit B – 32. The specific indicators of the measurement carried out are:

- Coverage of the measured distance - 1450 ÷ 1650mm; Discrete distance value – 0,1mm; absolute distance measurement error, ± 0,5mm;
- 2)Rotation Angle Measurement Range, 0 ÷ 360°; Discrete Angle Value, 0,0001°; Absolute Rotation Angle Measurement Error, ± 0,5°.

DISCUSSION

The most important indicators for correct and successful measurement are two: 1) achieving high resolution (resolution of the equipment used) and 2) achieving precise accuracy. The results obtained show that there is no significant change in the geometric distances of the Core barrel, compared to the passport data. It is assumed that until the next such measurement (after 4 years) there will be no (significant) change in the geometric distances.

CONCLUSION

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.

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