

NEUTRON PHYSICS CALCULATION FOR VVER-1000 ABSORBER ELEMENT LIFETIME DETERMINATION

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ABSTRACT

Absorber element (AE) with compound absorber has been operating in WWER-1000 power units since 1995. AE design meets operating organizations requirements for reliability, service life (to 10 years) and safety functions. Extension of AE service life up to 20 – 30 years by the complex of calculation and experimental work is an important problem of WWER new designs development.

The paper deals with the issues related to calculation determination of main factors that influence AE service life limitation – neutron flux and fluence onto absorbing and structural materials during extended service life.

1. PURPOSE AND DESIGN OF WWER-1000 ABSORBER ELEMENTS OF THE 90TH. OPERATING EXPERIENCE

WWER-1000 absorber element is a CPS structural component with several functions provided within a working member:

- core power control and maintenance at the specified level under normal operating conditions;
- core quick and safe transfer to subcritical state under anticipated operational occurrences and subcritical state maintenance;
- control of power xenon oscillations in case of their occurrence under transients.

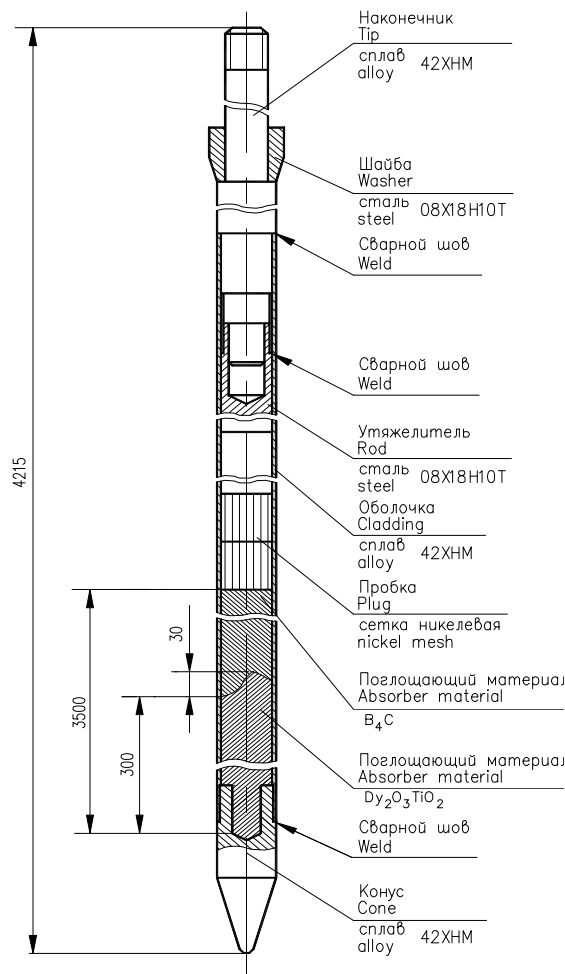


Figure 1 - Absorber element of WWER-1000 with a composite absorber

AE of new design with compound absorber (Fig. 1) is designed and manufactured at Moscow polymetal plant and has been in operation at WWER-1000 power units since 1995. This AE was developed in the 90-th as a part of the work on NPP power units transfer to more efficient fuel cycles, and also for decrease of CPS CR drop time during reactor operation at power. The problem specified is related to extension of fuel cycle length and as a consequence, hogging of shroudless FAs. The problem has also been decided by introduction of weighting material into AE.

The problems of CPS AR service life parameters enhancement were concurrently decided using n-γ absorber (dysprosium titanate) in AE bottom part because of its lower radiation swelling and gas release and also alloy 42XHM with enhanced radiation resistance used as a structural material.

Specified AE (refer Fig. 1) is now used in WWER-1000 RP designs, installed in WWER-1000 operating

power units and satisfies the following operating organizations requirements for:

- reliability – no one operational failure caused by a structure damage;
- safety functions – drop time under scram mode is provided not above 4 seconds for all units;
- efficiency – reliable power control under control mode and safe reactor shut-down under scram mode are provided during the whole specified service life considering absorber burn-up.

2. SUBSTANTIATION OF ABSORBER ELEMENT SERVICEABILITY FOR WWER NEW DESIGNS

Substantiation of AE service life extension from available 10 – up to 20 and even 30 years is the important problem of WWER new designs development. Available data on spent AE post-irradiation examination testify to the conservatism of the characteristics affecting serviceability as structural and absorbing materials. Some foreign products purposed for PWR and BWR reactors have specified service life up to 30 years.

Substantiation of AE service life extension to 20 – 30 years is planned by the complex of calculation and experimental work. Neutron-physics calculation is purposed, in particular, to determine main factors affecting limitation of AE assigned service life – ^{10}B burn-up (dgB10) and neutron fluence onto AE cladding.

3. DESIGN LIMITS

Post-irradiation examination proves that only up to 5 % of helium released during ^{10}B burn-up is supplied to gas collector in AE top part. Main share of helium is remained under the cladding causing B_4C swelling, and precise correlation between ^{10}B burn-up and AE cladding axial properties variation is observed. Observable powder sintering is above 25 % of isotope ^{10}B burn-up. ^{10}B powder turns into solid rode with a force onto cladding at burn-up 35 – 40 %. Limits for ^{10}B average cross-section burn-up not above 50 % are assumed in WWER-1000 design by the results of provided examinations /1/.

Loss of AE clad material ductility is proceeding in the course of irradiation. Alloy 42XHM with enhanced radiation resistance used as a structural material allows to increase fast neutron fluence limiting value ($E > 0,1$ MVe) to $6 \cdot 10^{22} \text{ cm}^{-2}$ /1/. Thus, more strict limitation of neutron fluence ($E > 0,1$ MVe) onto AE cone welded joint not above $3,4 \cdot 10^{22} \text{ cm}^{-2}$ is assumed in WWER-1000 design.

Post-irradiation examination shows highly non-uniform axial burn-up of ^{10}B . Observable ^{10}B burn-up is in AE bottom end under automatic control mode, thus limitation for AE operation under automatic control mode not above 3 years is assumed in WWER-1000 design. Increase of AE operation in control groups shall be also analyzed for total service life extension. Characteristics optimization can be also provided due to decrease of radiation load onto boron carbide by increase of absorbing part from dysprosium titanate (ref. Fig. 1).

4. CALCULATION PROCEDURE

Calculations of AE irradiation characteristics are provided using spectral codes for neutron transfer equation solution in multigroup approximation considering detailed description of core fragment and top reflector geometry. Verified code SAPFIR_95 is used for the purposes specified, in particular, for substantiation of AE for WWER-1000 designs /2/. FA 3-D geometrical model (Fig. 2) is assigned for calculation of radiation load onto AE absorber and cone. Model bottom (active fuel) part is a source of neutrons and top part describes fuel rod gas compensation volumes, the space between fuel rod top plugs and FA top nozzle, the FA top nozzle and comprised guiding channels with AE.

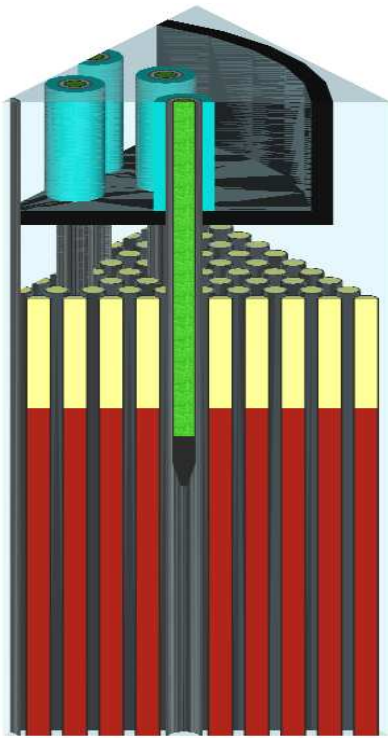


Figure 2-Spatial model of FA comprising AE

The results of core fragment model calculation are normalized by the distributions realized as a result of fuel cycles calculations for determination of neutron fluences and ^{10}B burn-up depth depending on CPS CR position in the core. The following parameters affecting neutron flux under specified operating conditions are considered:

- depth of control rod group insertion and, respectively, power of FA calculated layer comprising AE with absorbing material;
- fuel burn-up depth in FA specified calculated layer;
- boric acid concentration in the coolant.

Present design approach is based on determination of AE service life as a scheduled period, exactly – determination of AE permissible operating years under scram and automatic control modes. Thus, design calculation procedure provides a certain degree of conservatism for evaluation of radiation characteristics. For example, fixed position of automatic CR group is considered during fuel cycle; power of FA with inserted automatic CR group or with EP group above is assumed maximum of

power distributions realized in the fuel cycle calculation, etc.

Determination of absorber element ^{10}B maximum axial burn-up point can be considered as a specific problem. Thermal neutron burst in the area of fuel rod gas compensating volumes is observed when absorber above the fuel is unavailable. Dependence of neutron flux onto WWER-1000 AE cone from CR CPS position above the core is in particular presented in paper [3]. Thus it is shown, that the area of thermal neutron flux maximum density is at the level ~ 8 cm. ^{10}B burn-up local maximum control requires to prove or disprove the assumption that "critical" point of AE partially inserted into the core is above the core.

Figure 3 shows absorber (B_4C) thermal neutron flux density axial distribution for AE inserted into the core to 80 cm. The calculation is provided for the core fragment (ref. Fig. 2) with neutron reflecting conditions on fragment boundary surfaces and FA fixed power. In AE bottom (40 cm) is located absorber based on dysprosium titanate; ^{10}B burn-up is not considered. Maximum of thermal neutron flux in AE for ^{10}B initial concentration is observed in the point above the core of the model considered. The minimum period of AE radiation load recording is 1 year. Figure 4 presents absorber (B_4C) thermal neutron fluence axial distribution in AE after 8200 eff.h of radiation exposure and boron carbide thermal neutron flux density distribution to the moment of calculation termination obtained using the calculation model above. Neutron flux and fluence maximum values in the distributions

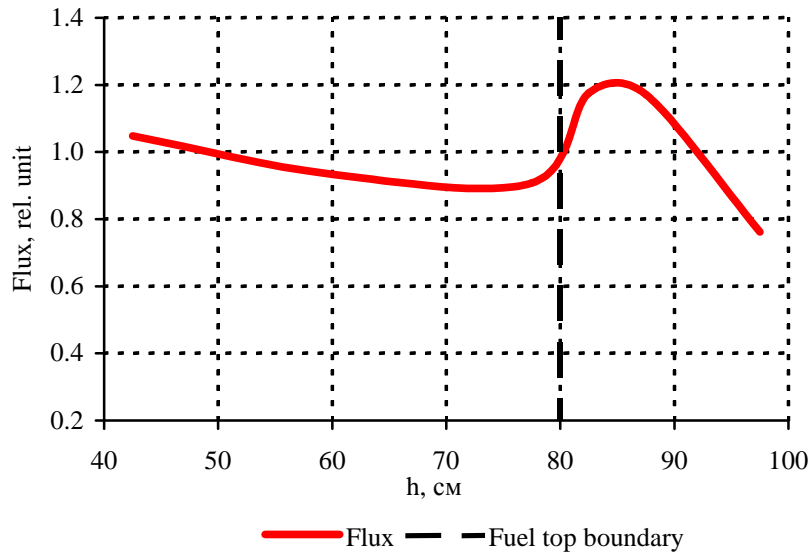


Figure 3 – Absorber (B_4C) thermal neutron flux axial distribution with AE inserted in the core to 80 cm. ^{10}B burn-up is not considered.

presented are realized in the core absorber bottom layer. Peak point observable displacement is explained by the higher intensity of AE ^{10}B burn-up in the core. Thermal spectrum of neutron energy distribution is above the core, respectively, one of the causes of ^{10}B lower burn-up in the area specified is neutron higher blockage in the absorber material. Thermal neutron fluence increase and ^{10}B burn-up, respectively, under AE further radiation exposure will also predominate for absorber bottom layer.

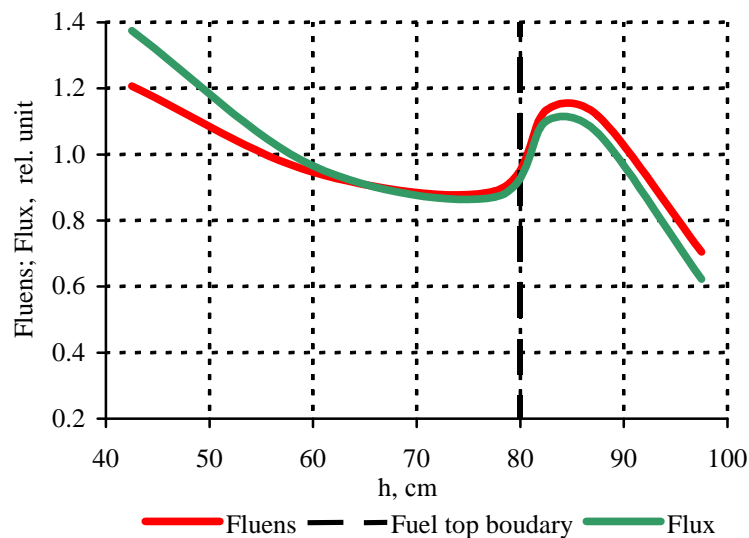


Figure 4 – Absorber (B_4C) thermal neutron fluence and ^{10}B burn-up axial distribution in AE inserted in the core to 80 cm. Radiation exposure time – 8200 eff. h.

Presented results are obtained under steady fixed power of calculation model reactor top part. Actually maximum power displacement from the core center to peripheral areas is observed at EOC, that presumably can result in the shift of thermal neutron flux maximum in the boron carbide to the area above the absorber lower boundary at EOC. The effect specified was not considered in detail but an expert judgment at the present stage can assume that

maximum ^{10}B burn-up at the end of the first year of AE radiation exposure is nevertheless realized in B_4C low layer at the boundary with the area of dysprosium titanate absorber.

5. BASIC CALCULATION RESULTS

Figure 5 shows calculation results of neutron fluence ($E > 0,1 \text{ MVe}$) on AE cone for different ratios of AE irradiation periods in EP and automatic CR groups under fuel cycle operation with one annual refueling. Provided calculation results show significant rate of fluence accumulation under AE irradiation in EP group, thus, AE service life can be extended to 20 years with specified limit (not above $3,4 \cdot 10^{22} \text{ cm}^{-2}$) only under the condition of AE continuous operation in the specified group within the time specified. Reduction of anticipated fast neutron fluence onto AE cone in EP group is possible due to increase of the distance from the fuel top boundary, that, however, is not supposed to be realized because FA with increased fuel stack is introduced in WWER-1000 design [4]. Experimental testing is required to verify possible increase of specified limiting fluence.

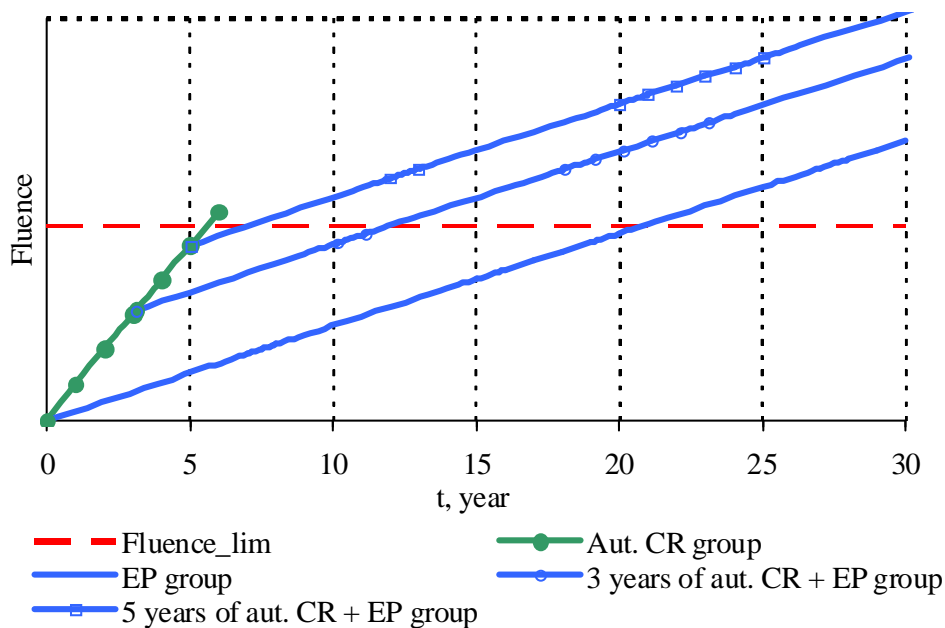


Figure 5 - Fast neutron fluence on AE cone in EP and automatic CR groups within the service life

Automatic CR group position in the core is of significant importance for determination of life characteristics for AE with B_4C absorber element. For ^{10}B burn-up lowering the possibility of absorber dysprosium titanate part increase to 50 cm is analyzed to provide absorber B_4C coming out of the core with automatic CR group position at elevation 90 %. Higher increase can result in significant lowering of automatic CR group differential worth and is not considered at present.

Figures 6 and 7 show calculation results for two fixed positions of automatic CR group within the ranges of recommended positions under reactor operation at nominal power – 70 and 90 % from the core bottom.

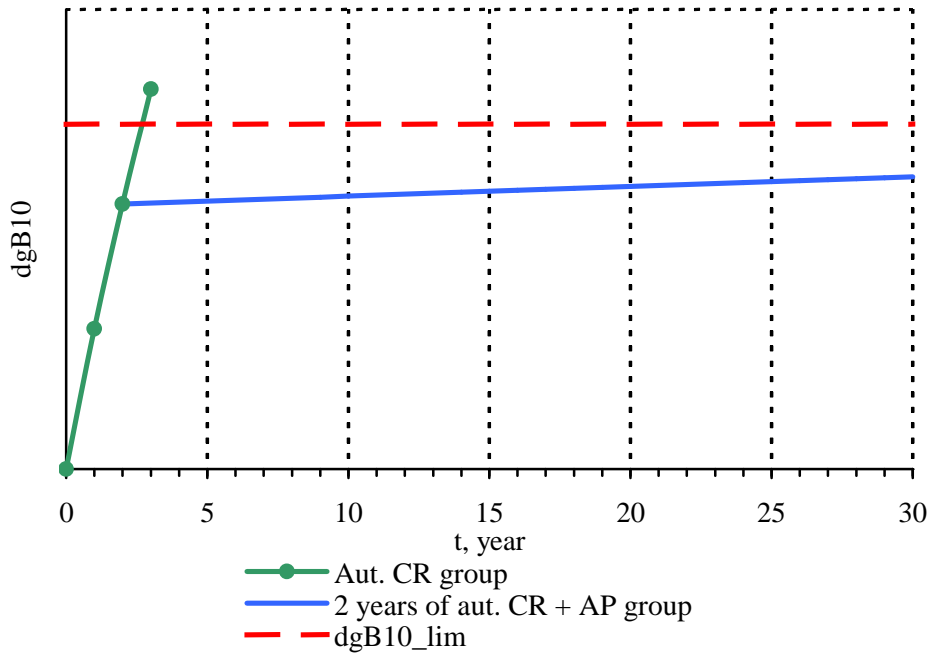


Figure 6 - Burn-up of isotope ^{10}B in AE absorber material in automatic CR and EP groups within the service life. Automatic CR fixed position for burn-up calculation is 70 % from the core bottom

Figure 6 shows that permissible time of AE boron exposure in automatic CR group at elevation 70 % shall be not above two years. Figure 7 shows that boron carbide exposure in automatic CR group at elevation 90 % and dysprosium titanate absorbing part length 50 cm allow AE use in automatic CR group up to seven years and AE total life up to 30 years according to ^{10}B burn-up characteristics.

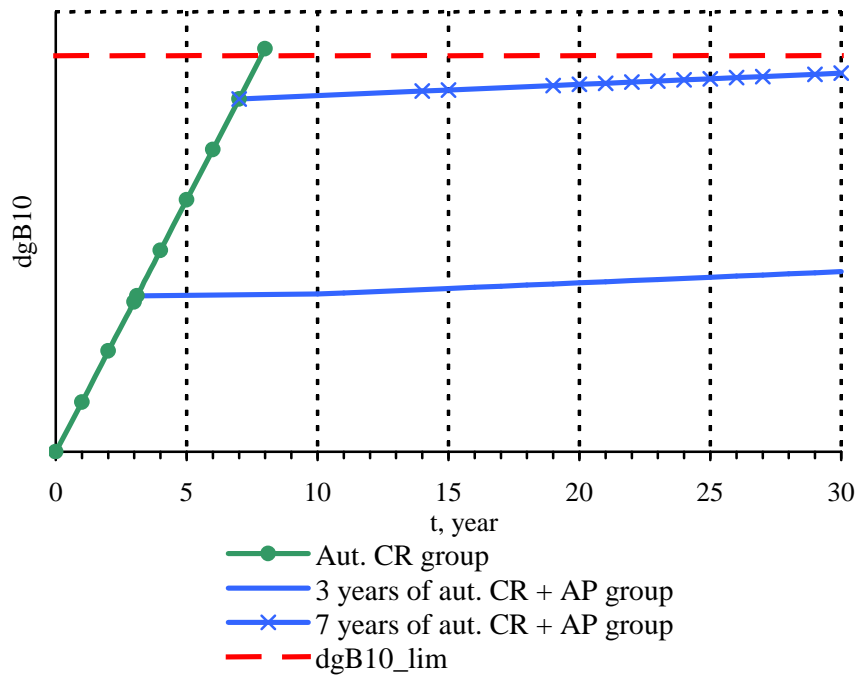


Figure 7 - Burn-up of isotope ^{10}B in AE absorber material in automatic CR and EP groups within the service life. Automatic CR fixed position for burn-up calculation is 90 % from the core bottom

6. CONCLUSION

Positive operating experience of WWER-1000 compound AE (bottom part of dysprosium titanate and top part of boron carbide) has been accumulated to the present time. This reference experience is used for prospective problem of the service life extension to 20-30 years.

Substantiation of AE service life extension to 20 – 30 years is planned by the complex of calculation and experimental work. Neutron-physical calculation, in particular, shall determine main factors affecting AE specified service life limitation – ^{10}B burn-up and neutron fluence onto AE cladding.

Neutron-physical calculations based on design approach prove that the most important factor for service life extension to 20-30 years is fast neutrons fluence on AE cone welded joint. Experimental examination is required to prove the possibility for increase of the limiting fluence assumed in WWER-1000 design.

Significant influence on service life determination for AE with boron carbide as an absorber is provided by CPS CR group position in the core (provided calculations prove that isotope ^{10}B maximum burn-up is in AE boron carbide bottom layer under operation in automatic CR group). The procedure of operating monitoring and AE operating characteristics processing at NPP is required to prevent excessive conservatism for service life determination. Operational analysis of each CPS CR shall include:

- recording of main parameters influencing neutron flux density under specified operating conditions (depth of automatic CR group insertion, power and depth of fuel burn-up in FA with AE, primary coolant boric acid concentration);
- calculation of maximum neutron fluence onto AE cladding and isotope ^{10}B burn-up for end of each fuel cycle;
- comparison of radiation exposure characteristics with specified limiting values and making a decision of CPS CR further operation.

ABBREVIATIONS ACCEPTED

| | |
|-----|-------------------------------|
| AE | absorber element |
| AR | absorbing rod |
| CPS | control and protection system |
| CR | control rod |
| EOC | end of fuel cycle |
| EP | emergency protection |
| FA | fuel assembly |

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