# E110M Alloy Fuel Rod Claddings in-Reactor Tests in Water-Cooled Reactors and Post-Irradiation Examination Results


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## Abstract

The results of trial operation of E110M alloy fuel rod claddings as part of TVS-2M type fuel assemblies in unit 2 of Balakovo NPP VVER-1000 reactor during 3 18-month-long cycles were analyzed. Inspection data of three experimental TVS-2M, which reached a burn-up of (55 – 60) MW·day/kgU, testifies to the high shaping and corrosion resistance of E110M alloy in comparison with other cladding materials.

This report presents the results of non-destructive tests in SC «SSC RIAR»: oxide film growth kinetics on fuel rods and samples received by eddy current method, the state of their outer surface from visual observations and data on diameter measurements and elongation of fuel rods in the process of reactor tests. Destructive post-irradiation examinations according to metallography confirm the results of eddy current measurements of the oxide film thickness on studied alloys fuel rod claddings.

The results of post-irradiation examinations in SC «SSC RIAR» are compared with data from non-reactor examinations of fuel rod cladding samples.

Obtained results show that the best combination of properties for fuel claddings under irradiation in a VVER conditions are demonstrated by E110M alloys.

In addition, the MIR research reactor was used for RAMP tests of fuel rod claddings from E110M and E110opt alloys. The RAMP tests results confirm the reliability of fuel claddings made of E110M alloy.



**Keywords:** E110M alloy, fuel rod cladding, non-destructive tests, destructive post-irradiation examinations.


## Introduction

Zr-Nb and Zr-Nb-Sn-Fe type alloys are used as fuel cladding materials in VVER and PWR reactors. The E110 [1] and E635 [2] alloys are used for VVER reactors and M5 [3] and ZIRLO [4] alloys are used in PWR reactors. Other alloys of the mentioned above systems are being developed and tested in research and commercial reactors [5-8]. One of the main goals of this type development is to enhance corrosion and creep strain resistance of the zirconium fuel rod claddings.

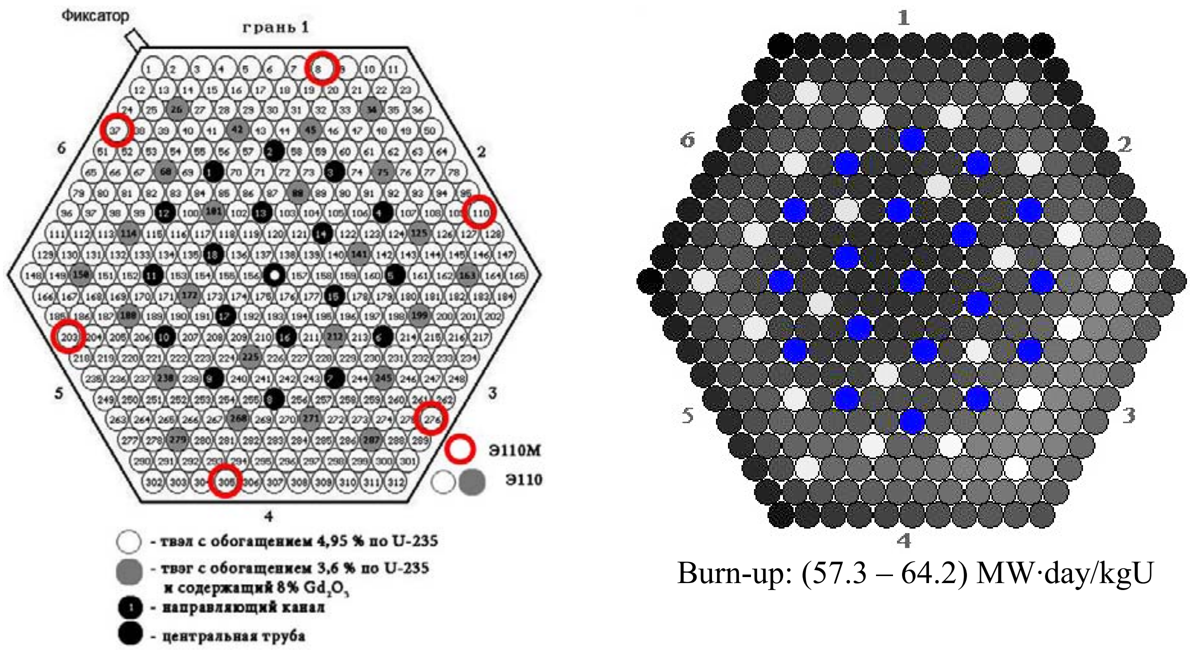
To evaluate the characteristics of the developing alloys, tests of experimental assemblies in industrial and research reactors are used.

This paper presents the results of operational characteristics of fuel element claddings made of E110M alloy irradiated in a WWER-1000 reactor in the second unit of Balakovo NPP. In addition, in the framework of the paper, comparative RAMP tests of fuel claddings made of E110M and E110opt alloys in the MIR research reactor were carried out.

## Materials and test conditions

The material for non-destructive and destructive examinations was the experimental and industrial fuel rods claddings made of E110M and E110 alloys of TVS-2M № 485408750 (Figure 1). TVS-2M № 485408750 was operated at the second unit of the Balakovo NPP, comprising (20 – 22) fuel loads up to an average fuel burn-up of 59.73 MW·day/kgU. Duration of operation amounted to ~ 1462 eff. days.

For destructive examinations, fuel rod № 37 (62.96 MW·day/kgU) with E110M alloy clad-




a) b)

**Figure 1. Cartograms of the fuel rods placement (a) and average burn-up (b)**

**Table 1. Alloying composition of fuel rod claddings material**

| Alloy | Nb, % | Sn, % | Fe, % | O, % |
|---|---|---|---|---|
| E110opt | 1.05 | - | 0.054 | 0.094 |
| E110M | 1.02 | - | 0.092 | 0.126 |
| E110 | 2.45 | - | 0.035 | 0.069 |

ding and adjacent regular fuel rod № 51 (62.94 MW·day/kgU) with E110 alloy cladding were selected.

In addition, the MIR reactor was used to irradiate TVS-PWR-2experimental assembly containing fuel rods with claddings of 9.5×8.33 mm made from various alloys, including E110opt and E110M alloys. Irradiation was carried out while maintaining the operating conditions of exploitation, as closely as possible to the conditions of the PWR reactor. After achieving a maximum fuel burn-up of 35.7 MW·day/kgU, fuel rods were extracted and sent to conduct a RAMP test (Experiment NG6K). Alloying composition of fuel rod claddings material is presented in Table 1.

## PIE results

### 1. Fuel rod claddings after VVER-1000 irradiated

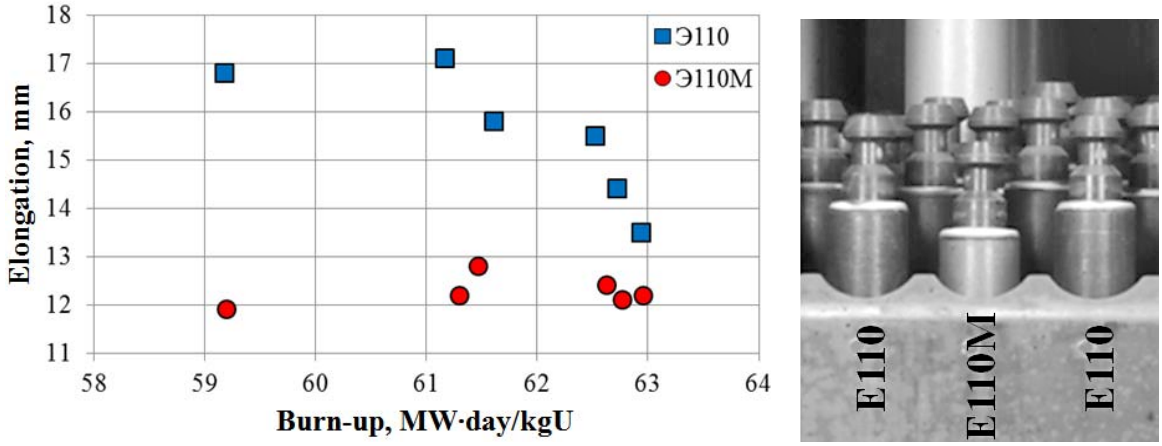
To determine the resistance of experimental fuel rods to irradiation shaping, it is necessary to analyze the results on the elongation of fuel rods and the change in their diameter, taking into account the burn-up of fuel.

The length of the fuel rods was determined by the combined method. The difference in height of all the fuel rods in the assembly and the absolute length of the fuel rods after disassembling the fuel assembly were measured.

Figure 2a shows the dependence of the elongation of experimental fuel rod claddings made of E110M alloy in comparison with the industrial fuel rod claddings made of E110 alloy.

Fuel rod claddings made of E110M alloy, the average elongation of which is 12.3 mm, have the highest resistance to irradiation shaping. The average elongation of the fuel rod claddings made of E110 alloy is at the level of 15.5 mm.

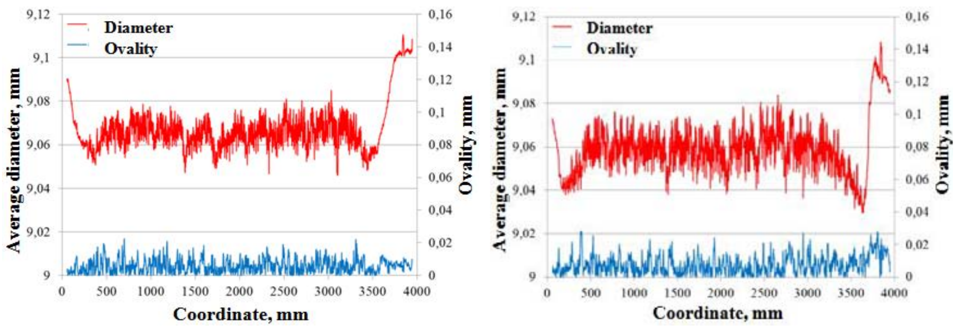
Figure 2b shows the appearance of the TVS-2M No. 485408750 assembly upper part from the side of face № 5. The figure clearly shows the difference in height between the experimental and standard fuel rods claddings. It can be seen that the fuel rod claddings made of E110M alloy have




a) b)

**Figure 2. Elongation of experimental and industrial fuel rod claddings**

from face № 5 in comparison with the adjacent standard fuel rod cladding made of E110 alloy.




a) b)

**Figure 3. Change of diameter and ovality along the length of fuel rod claddings from E110M (a) and E110 (b) alloys**

the smallest elongation associated with irradiation shaping.

Measurement of the fuel rod claddings outer diameter was carried out on an automated stand equipped with linear displacement sensors.

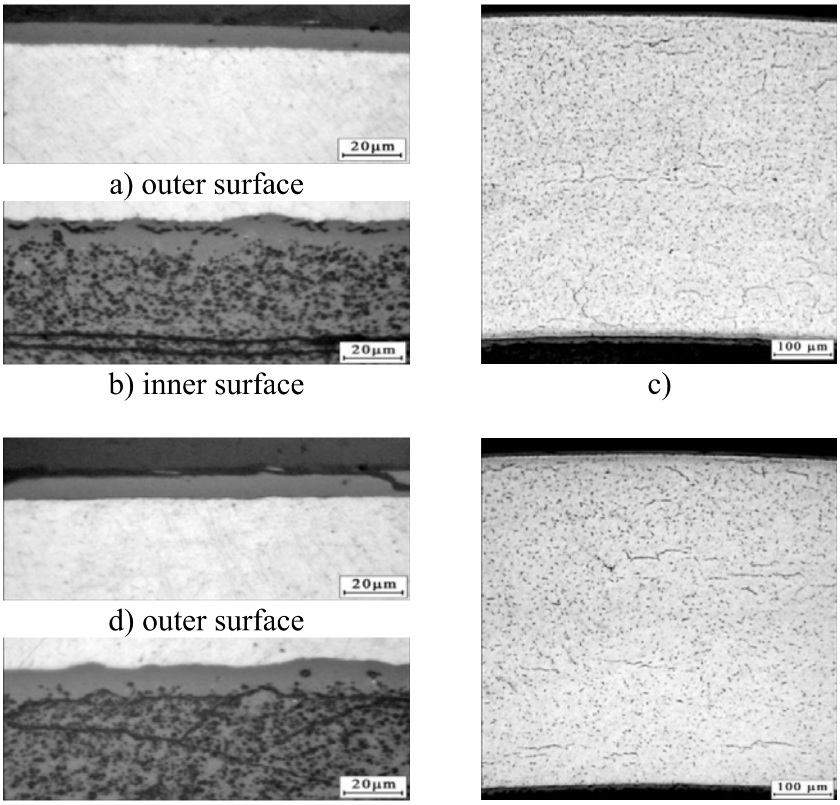
Figure 3 shows profilograms of an experimental fuel rod cladding made of E110M alloy from face № 5 in comparison with the adjacent standard fuel rod cladding made of E110 alloy.

The profile of the change in diameter along the fuel rods length is characterized by the presence of corrugations and a section of creep deformation after pellet-cladding interaction. According to the location of the spacer grids, the diameter of the cladding is smaller compared with the adjacent areas.

The height of the corrugations for fuel rod cladding made of E110 alloy and pellet 7.6×1.2 mm is averages ~ 12 μm, and the creep strain after pellet-cladding interaction is in the range (0.016 – 0.029) mm. On the fuel rod cladding made of E110M alloy, the form change of the cladding is less pronounced. The creep deformation after pellet-cladding interaction is in the range (0.003 – 0.014) mm, the average height of the corrugation is 6 μm.

The oxide film thickness was measured using a Fischerscope MMS® instrument equipped with an Et3.3-D09A surface mounted eddy current probe.

During operation in the VVER-1000 reactor, oxide film thickness on the outer surface of the fuel rod cladding increases with the height coordinate and reaches its maximum value in the area (3000 – 3300) mm. Above this coordinate, oxidation decreases, and in the area corresponding to the plenum location reaches minimum values. The maximum oxide film thickness for standard E110 alloy is in the range (10 – 16) μm, for alloy E110M – (15 – 19) μm.

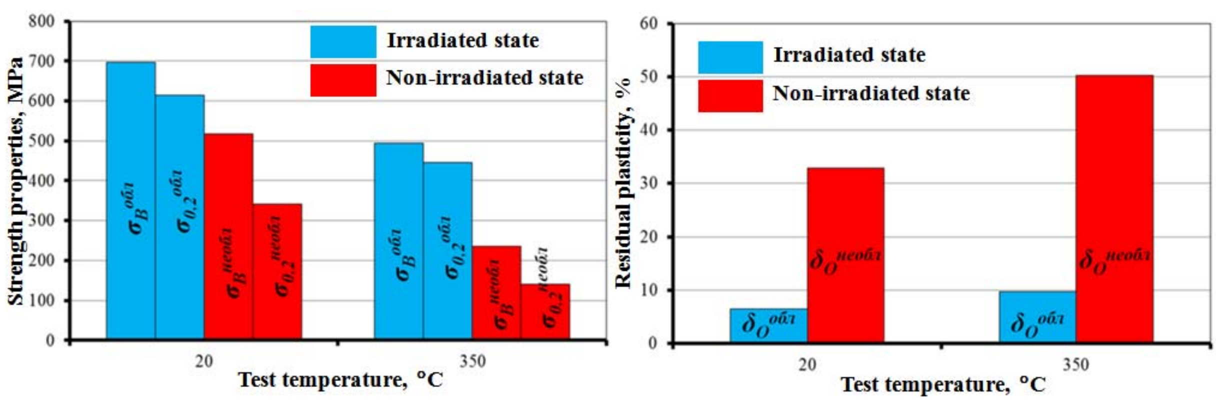


a) outer surface
b) inner surface
c)
d) outer surface
e) inner surface
f)

**Figure 4. Macro- and microstructure of the of the fuel rod cladding cross section № 37 from E110M alloy (a, b, c) and № 51 from E110 alloy (d, e, f) at a height of ~ 3100 mm**

**Table 2. Cladding mechanical properties in the transverse and longitudinal direction**

| Alloy | Transverse direction | | | Longitudinal direction | | |
|---|---|---|---|---|---|---|
| | Test temperature 20°C | | | | | |
| | **σB, MPa** | **σ0,2, MPa** | **δo, %** | **σB, MPa** | **σ0,2, MPa** | **δo, %** |
| E110M | 683 – 734 | 606 – 689 | 6.7 – 15 | 649 – 769 | 579 – 669 | 3.2 – 8.3 |
| E110 | 520 – 587 | 486 – 551 | 10 – 17 | 576 – 677 | 507 – 604 | 6.2 – 9.0 |
| | Test temperature 350°C | | | | | |
| E110M | 465 – 518 | 453 – 509 | 10 – 17 | 411 – 548 | 395 – 487 | 6.6 – 12 |
| E110 | 353 – 392 | 352 – 380 | 14 – 17 | 410 – 458 | 381 – 429 | 5.7 – 8.9 |




a) b)

**Figure 5. Comparison of the mechanical characteristics of the fuel rod cladding samples from E110M alloy in irradiated and non-irradiated states (longitudinal samples)**

The metallographic studies results show that the corrosive state of the fuel claddings №№ 37 and 51 from E110M and E110 alloys, respectively, is characterized by the presence of oxide film, both on the inner and on the outer surface. On the outer surface of the claddings, the oxide film is tightly adhered to the metal. The oxide film thickness is uneven in height of the fuel rod. At the bottom of the fuel rods, the oxide film thickness is (5 – 6) μm, and at an altitude level of ~ 3100 mm it reaches values of 10 μm (Figure 4).

The oxide film on the inner surface of the fuel cladding made of E110M alloy has a uniform thickness along the fuel rod height and does not exceed 13 μm. At coordinate 3707 mm, the oxidation of the inner surface of the cladding is not visually detected. Oxidation of the inner surface of the fuel cladding № 51 from E110 alloy is similar to that of a fuel rod № 37.

In the microstructure of transverse specimens from fuel rod claddings №№ 37 and 51, point and extended hydrides were found at all height levels. However the hydrogenation of the claddings is insignificant.

The hydrogen content in the claddings was determined by the high-temperature extraction in a stream of inert carrier gas method using the ELTRA OH 900 gas analyzer. As follows from the analysis results, the hydrogen content in the fuel rod claddings increases with increasing height coordinate, and in the plenum has a maximum value not exceeding 0.005 and 0.006 wt.% for fuel rods №№ 37 and 51, respectively.

Mechanical tests of the axial and ring samples of fuel rod claddings №№ 37 and 51 from E110M and E110 alloys, respectively, were performed on the Zwick Roell Z010 universal testing machine at temperatures of 20 and 350° C.

The main results of the mechanical tensile tests of the fuel rod cladding samples made of E110M and E110 alloys are given in Table 2.

The strength characteristics of the fuel rod cladding made of E110M alloy are on average 1.3 times higher than the strength characteristics of the fuel rod cladding from E110 alloy. The ductility characteristics (total elongation) remain approximately at the same level, both at room temperature and at elevated test temperatures.

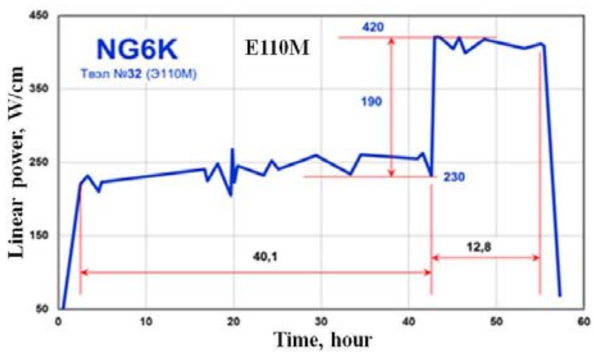
Figure 5 presents a comparison of the mechanical characteristics of the fuel rod cladding samples from E110M alloy in irradiated and non-irradiated states.

Neutron irradiation in a VVER-1000 reactor led to the hardening of the fuel cladding material from E110M alloy. At room temperature, the strength value increased by 1.4 times, the yield strength value by 1.8 times, while the value of the residual plasticity decreased 5.1 times. At a temperature of 350 ° C, the tensile strength value increased by 2.1 times, the yield strength value by 3.2 times, and the value of residual ductility decreased by 5.2 times.

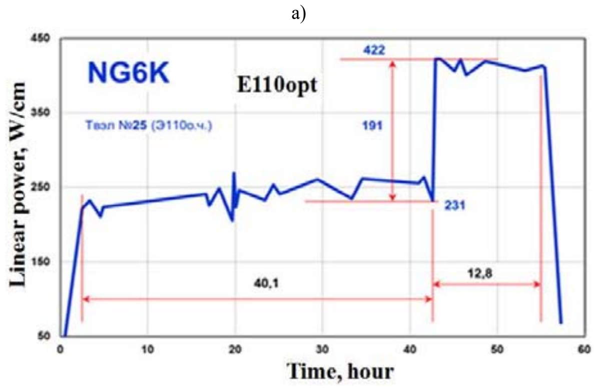
## 2. RAMP tests

The main objective of the RAMP experiment was to compare the behavior of fuel rod claddings from E110opt and E110M alloys in non-normal exploitation conditions with the aim of calculating and experimental substantiation of the fuel TVS-K for PWR reactors.

Figure 6 shows the change in the maximum linear power in a fuel rods № 32 (E110M) and № 25 (E110opt).




a)




b)

**Figure 6. Change in the maximum linear power in a fuel rods № 32 (E1110M) (a) and № 25 (E110opt) (b)**

The maximum linear loads were reached on the fuel rods № 25 (E110opt) and № 32 (E110M) and amounted to 422 W/cm and 420 W/cm, respectively. The maximum relative deformation of the fuel rod cladding № 25 (E110opt) – 1.01% and fuel rod cladding № 32 (E110M) – 0.91%. All fuel rods retained tightness.

## Conclusion

1. The reactor tests and post-irradiation examinations results of experimental claddings from E110M, which had been used as part of TVS-2M in VVER-1000 reactor of Balakovo NPP unit 2 during 3 18-month cycles showed that:

- fuel rod claddings made of E110M alloy, the average elongation of which is 12.3 mm, have the highest resistance to irradiation shaping. The average elongation of the fuel rod claddings made of E110 alloy is at the level of 15.5 mm. The creep deformation after pellet-cladding interaction for E110M alloy is in the range (0.003 – 0.014) mm, and less that for E110 alloy claddings which is in the range (0.016 – 0.029) mm;
- the maximum oxide film thickness for standard E110 alloy is in the range (10 – 16) μm, for alloy E110M – (15 – 19) μm;
- an increase in the oxidation degree of the investigated fuel rod claddings leads to a linear increase in the absorbed hydrogen fraction during fuel assembly operation, which does not exceed 50 ppm;
- the strength characteristics of the fuel rod cladding made of E110M alloy are on average 1.3 times higher than the strength characteristics of the fuel rod cladding from E110 alloy. The ductility characteristics (total elongation) remain approximately at the same level, both at room temperature and at elevated test temperatures.

2. According to the results of the RAMP tests shown: the maximum linear loads were reached on the fuel rods № 25 (E110opt) and № 32 (E110M) and amounted to 422 W/cm and 420 W/cm, respectively. The maximum relative deformation of the fuel rod cladding № 25 (E110opt) – 1.01% and fuel rod cladding № 32 (E110M) – 0.91%. All fuel rods retained tightness.

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