Integration of Post-Irradiation Examination Results of Failed WWER Fuel Rods

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1. Introduction

Cases of leakage and failure of production-type WWER fuel assemblies were registered during whole operation period of the WWER reactors. Here, general amount of fuel failure decreases constantly. The achieved factor of Russian fuel reliability is $1.5 \cdot 10^{-6}$ (for WWER-440 during 1997-2001) [1].

However, for a number of reasons some fuel assemblies with leaky fuel rods can be located in the core for certain period of time. It leads to the increase of the coolant activity and other negative consequences that influence the NPP safety and efficiency as a whole. That is why the urgent task is to determine the causes of WWER fuel rod failures and to reveal the main dependences of the failed fuel rod behavior and state on the damage characteristics and duration of their operation in the core.

2. Classification of Registered Fuel Rod Cladding Damages

In this paper the term "initial damage" means only through defects that caused leakage of the fuel rod claddings. The revealed initial through defects caused by accelerated corrosion, debris-damage and fretting-wear are different in their appearance (Figure 1) and there was no any difficulty in their identification. Besides through defects, different non-through defects of the fuel rod claddings (debris, fretting, etc) were observed but they are not concerned in this paper.

In the presence of the "initial defect" the term "secondary damage" ("secondary defect") means defects generated under the effect of coolant penetrated into the fuel rod trough the initial defect. These defects are as follows: fragile breakaway of plugs, visually registered through cracks and hydride spots spreading on the outer surface of cladding.

3. Generalized Results of Post-Irradiation Examination

By now 12 leaky WWER fuel assemblies (according to NPP sipping control system) have been examined at SSC RF RIAR. They are 5 WWER-440 and 7 WWER-1000 fuel assemblies. The diagram of damage causes is presented in Figure 3. The fuel assemblies were operated at different NPPs within the period from one to four fuel cycles (average fuel burn-up range is form 13.1 up to 46.8 MWd/kgU).

After the perforation of the fuel rod claddings occurred by any of the above mechanisms the coolant enters inside the fuel rod through the primary defect. Here radiolysis and thermal dissociation of H_2O vapors takes place. Oxygen is bounded chemically as a result of oxidation of fuel pellets (fission products) and the inner surface of cladding. Free hydrogen penetrates into the cladding, where Zr hydrides generate. Such hydrogenizing is possible either in the defect area or in the area of ZrO_2 continuity damage or in the places with thin protective oxide film.

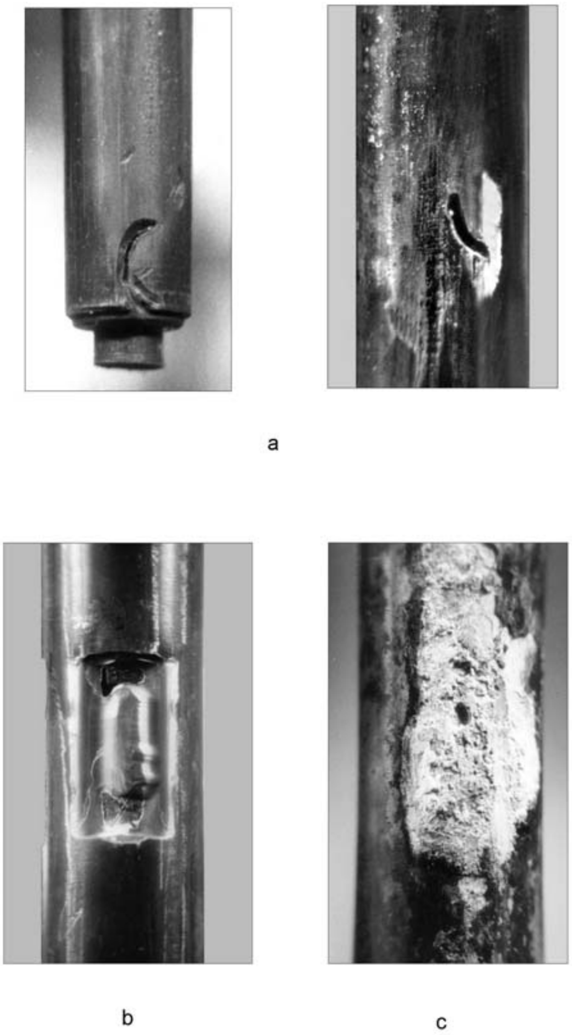

Figure 1. Primary damage of the fuel rod claddings: a) debris-fretting; b) "grid-rod" fretting; c) corrosion damage

film. Further, these areas could become concentrators of hydrogen and it leads to vaster local hydrogenizing. Local increase of the cladding diameter (blisters) occurs as a result of volumetric expansion of the generated hydrides (by ~16%) relative to initial Zr. Mechanical stress in the hydrogenated cladding causes brittle cracking [5-10].

As a rule, the areas of secondary hydrogenising of the WWER fuel rod claddings are spaced from the primary defects by ~2500-300 mm (Figure 4) and are often adjacent closely to the upper weld joints.

Evolution of secondary hydrogenizing process of the claddings depends greatly on the linear power of the defect fuel rods, period of their operation in the leaky state and on the dimensions of the primary defects. As a rule, there were no any precise data on the linear power of the leaky fuel rods and the moment of their perforation. That is why only evaluations of these parameters were used for plotting the dependences. These evaluations are based of the analysis of the diagram of the primary circuit coolant activity and calculation-experimental values of the fuel burn-up in the leaky fuel rods.

The analysis of the data obtained did no reveal any pronounced functional dependence of the distance between the primary and secondary cladding defects neither on the linear power, at which the fuel rods were operated, no on the period of their operation in the leaky state (Figure 5).

The detailed examination aimed at the determination of correlation between the degradation of defective fuel rod and parameters of the fuel operation (thermal flux and time up to the secondary failure) was performed by Locke.

Based on the data on the operation experience of defective fuel rods he obtained the threshold between the strong failure and slight damage known as “Locke boundary”. However, it should be mentioned that the types of fuel rods and methods of their fabrication examined by Locke were different from those of the WWER fuel. That is why, it is not quite correct to apply the “Locke boundary” to the WWER fuel rods.

Figure 6 presents the dependence of time of the secondary damage evolution on the linear power of the examined defect fuel rods. In spite of the considerable scattering of points a conclusion can be drawn that the time period of the significant secondary damage evolution is about 250±50 calendar days for the WWER fuel rods with slight through primary defects (~0.1-0.5 mm^2) operated in the linear power range 170-215 W/cm.

The degree of the fuel rod secondary degradation depends greatly not only on the position and type of the primary defect but also on its size. It is explained by the fact that in case of large through defects the speed of vapor penetration into the fuel rod is high. It leads to the generation of thicker protective oxide film on the inner surface of the claddings and makes difficulties for achievement of “critical” hydrogen concentration inside the fuel rods. Thus, no formation of the secondary defects occurred in two WWER-440 fuel rods with through damage of ~30 mm^2 during their operation within ~600 calendar days in the leaky state.

4. Conclusions

1. The main mechanism responsible for the majority of cases of the WWER fuel rod perforation is debris-damage of the claddings.
2. Debris-fretting of the claddings spread randomly over the fuel assembly cross-section and they are registered in the area of the bundle supporting grid or under the lower spacer grids along the fuel assembly height.
3. In the WWER fuel rods, the areas of secondary hydrogenizing of cladding are spaced from the primary defects by ~2500-3000 mm, as a rule, and are often adjacent closely to the upper welded joints

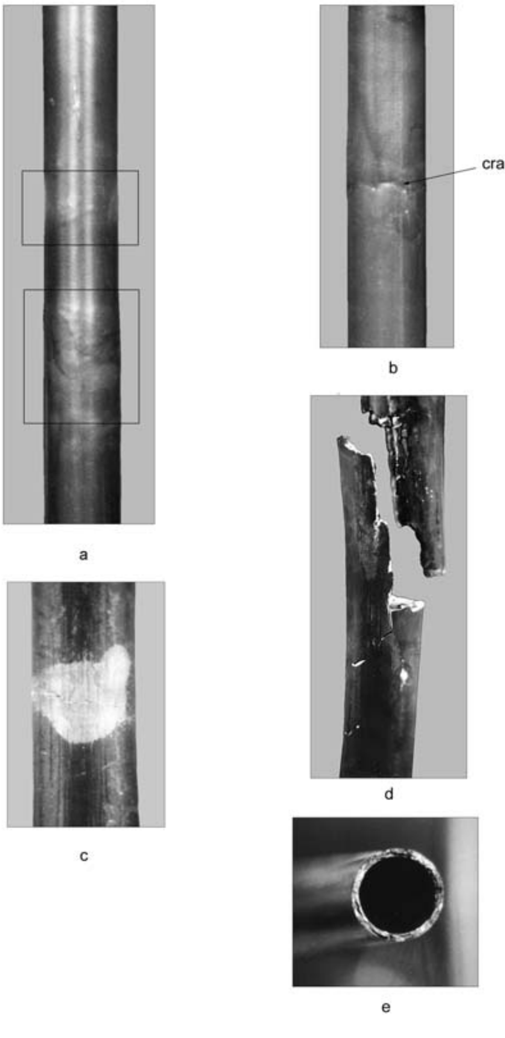

Figure 2. **Secondary damage of the fuel rod claddings: a) local diameter increase; b) crack; c) hydride spot; d) fracture of cladding; e) breakaway of the upper plug**

4. There is no pronounced dependence of the distance between the primary and secondary cladding defects neither on the linear power, at which the fuel rods were operated, no on the period of their operation in the leaky state.
5. The time period of the significant secondary damage formation is about 250±50 calendar days for the WWER fuel rods with slight through primary defects (~0.1-0.5 mm^2) operated in the linear power range 170-215 W/cm.
6. Cladding degradation taking place due to the secondary hydrogenising does not occur in case of large through debris-defects during operation up to 600 calendar days.

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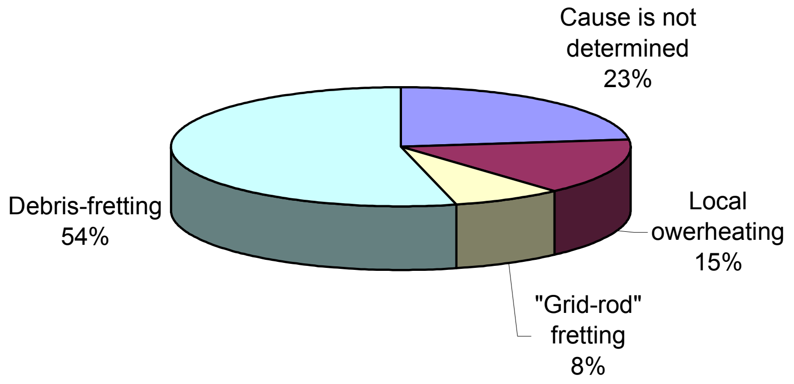

Figure 3. Causes of failure of the examined WWER fuel assemblies

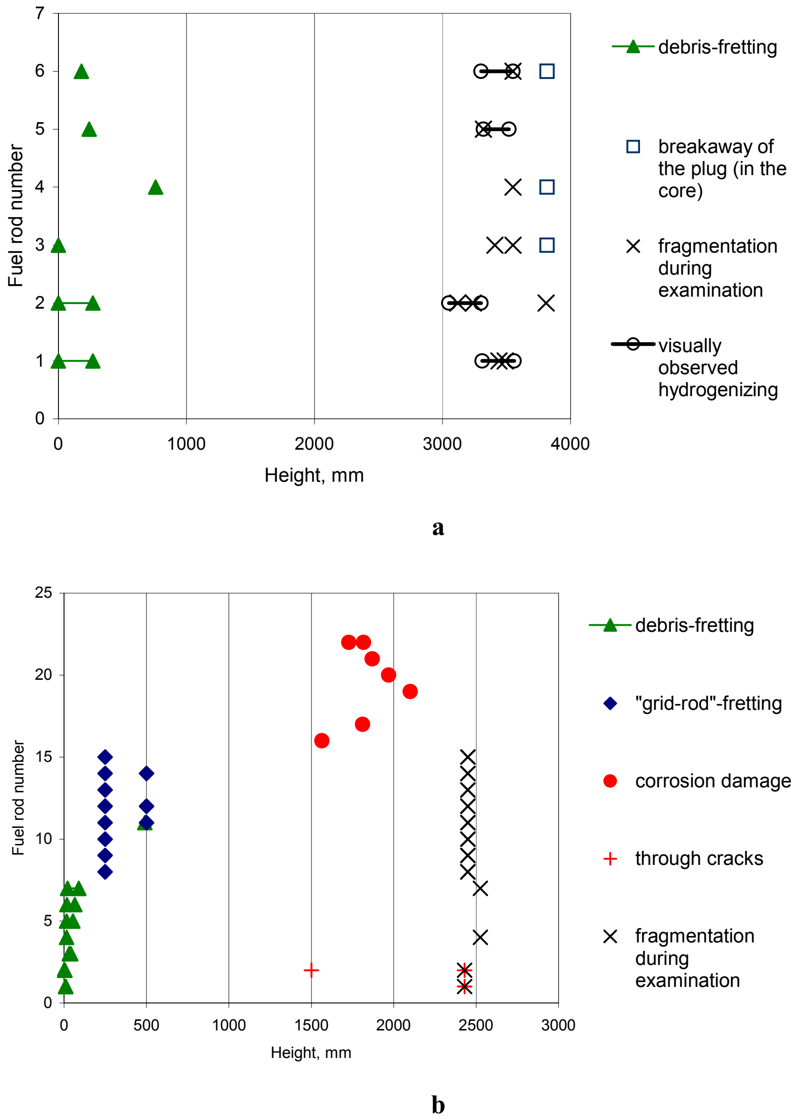

Figure 4. Location of the primary and secondary damage of the WWER-1000 (a) and WWER-440 (b) fuel rods

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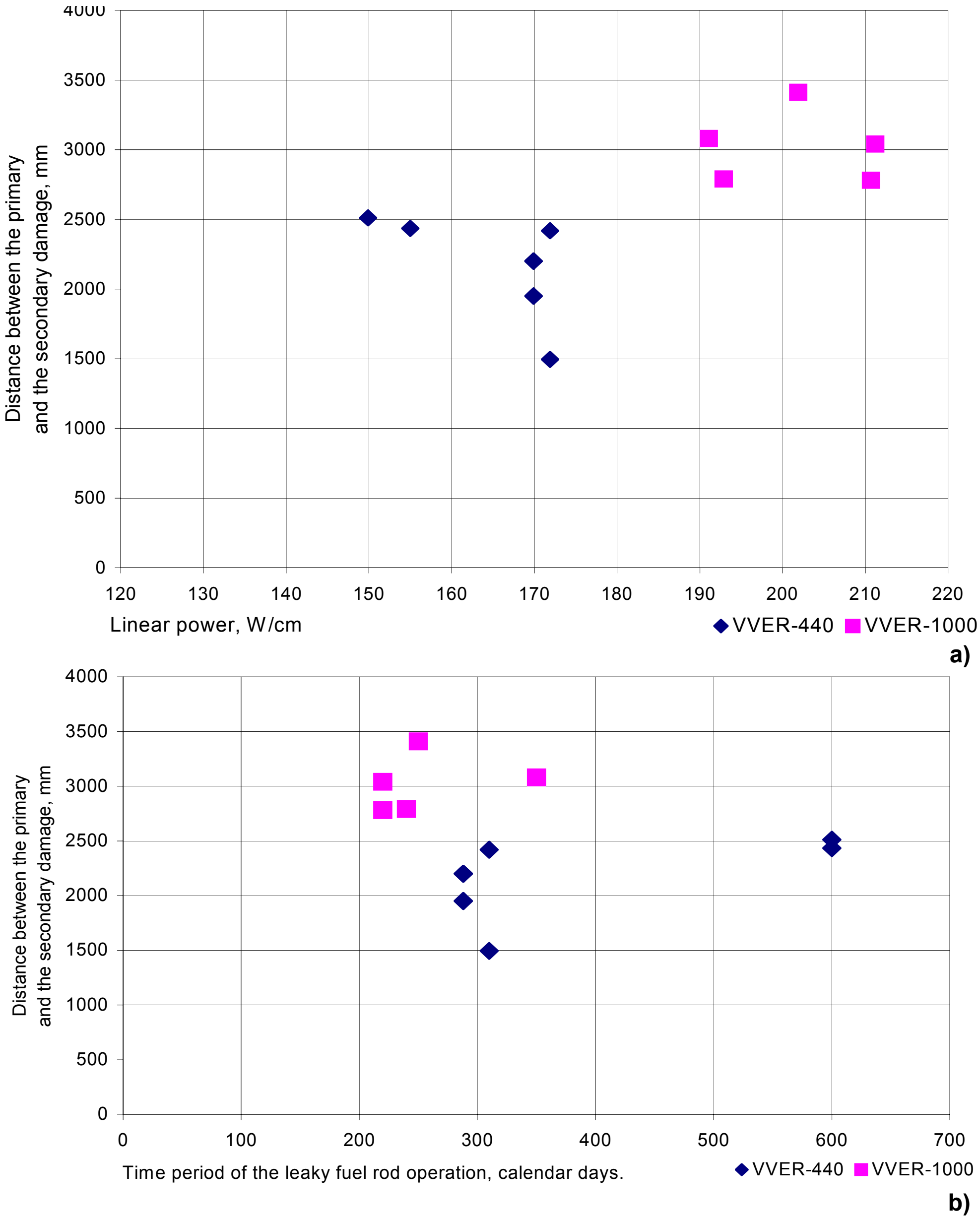

Figure 5. **Distance between the primary and secondary damage of fuel rods depending on LHGR (a) and operation period after the seal failure (b)**

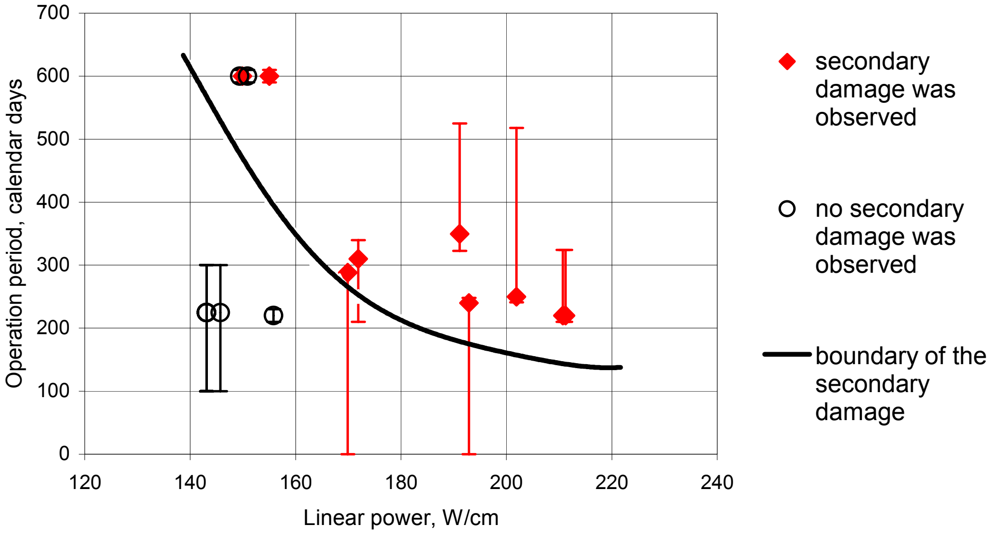

Figure 6. Secondary damage of the WWER fuel rods