Fuel Rod Behaviour at High Burnup WWER Fuel Cycles

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1. Introduction

Long and successful experience of WWER fuel operation based on experience of designing, experimental and calculation justification confirms sufficient reserves of improvement of WWER fuel parameters.

Russian fuel supplier JSC TVEL carries out an intense program to improve technical and economical parameters of WWER fuel cycles.

The main lines of fuel cycles modernization are as follows:

- Increase of fuel usage efficiency by going on to 5-6 year fuel cycle operation;
- Forcing of fuel assembly (FA) power (WWER-440);
- Decrease of heat rate ramps at fuel rods (FR) due to optimization of fuel reload scheme and modernization of FA design;
- As a result, application of load following mode of operation;
- Ensuring the safe fuel treatment, compensation of initial excess reactivity and core power flattening as a result of burnable absorber usage.

Fuel cycles modernization is carried out on the base of development of fuel rod and fuel assembly design.

The modern stage of WWER fuel operation is characterized by the following parameters of fuel burnup.

1.1. WWER-440

- UO_2 and $(U\text{-}Gd)O_2$ 2-nd generation fuel with increased loading mass is applied in 5-year fuel cycle with a portion of 6-year assemblies at Kolskaja NPP Unit 3 in 2002. Target burnups are as follows:
    - FA – 54 MWd/kgU;
    - FR – 63 MWd/kgU;
    - FR (Gd) – 55 MWd/kgU;
    - Fuel pellet (FP) – 70 MWd/kgU
    - FP (Gd) – 62 MWd/kgU;
- Pilot operation of 5-year cycle FAs during 6 years is successfully completed at Kolskaja NPP Unit 3 in 2002. Designed burnups were as follows:
    - FA – 58 MWd/kgU;
    - FR – 65 MWd/kgU;
    - FP – 74 MWd/kgU.

1.2. WWER-1000

- Pilot operation of advanced FA (TVS-2) started at Balakovo NPP Unit 1 in 2003. Target burnups are as follows:
    - FA – 55 MWd/kgU;
    - FR – 59 MWd/kgU;
    - FR (Gd) – 52 MWd/kgU;
    - FP – 64 MWd/kgU;
    - FP (Gd) – 56 MWd/kgU;
- Pilot operation of 4-year cycle alternative fuel assemblies (AFA) during 5 years is successfully completed with AFA burnup 52 MWd/kgU at Kalininskaja NPP Unit 1. Portion of AFAs operated during 5 years are reloaded for 6-year test operation with target FR burnup 66 MWd/kgU.

2. Modelling of High-Burnup Fuel

Application of modernized fuel cycles requires ensuring of fuel reliability that makes high demands of modeling of effects taking place in fuel during irradiation. These demands are formed according to factors such as increase of fuel target burnup, increase of fuel loading mass at FR, ensuring load following operation of NPPs.

Code START-3 intended for justification of WWER FR reliability under normal and off-normal conditions completely meets demands made of high-burnup fuel modelling.

For executing of FR efficiency calculations at modernized fuel cycles:

- Improved models are used;
- Prediction capability of code as a whole is tested;
- Universality of separate models is verified as applied to high burnup conditions of WWER fuel.

Experimental database for code verification includes in-reactor experiments and post-irradiation examination of more than 100 full-scale and refabricated WWER FRs irradiated to maximal burnups 70 MWd/kgU.

3. High Burnup Effects

High burnup has different influence on model consideration of some fuel parameters [1].

Properties requiring major modification or development of new models for high burnup fuel are as follows:

- Fuel thermal conductivity;
- Fission gas release;
- Fuel swelling;
- Formation of high burnup structure,

accounting for radial profile of volume heat rate and local burnup of fuel pellet.

3.1. Fuel Thermal Conductivity

Thermal conductivity dependence on burnup used in code START-3 is based on relations obtained in investigations of irradiated UO_2 and $(U\text{-}Gd)O_2$ fuel [2,3].

$$\lambda=\left(\frac{1}{A+B\cdot x+C\cdot T+F(Bu)+H(T)\cdot G(Bu)}+D\cdot T^4\right)\cdot f(p)$$

where:

λ – thermal conductivity, [W/m·K];

T – temperature, [K];

Bu – burnup, [MWd/kgU];

x – Gd_2O_3 content, wt.%;

$F(Bu) = a_1 Bu$ – effect of fission products in crystal matrix;

$G(Bu) = a_2 Bu^m$ – effect of irradiation defects;

$H(T) = 1/[1+a_3\exp(-Q/T)]$ – annealing of irradiation defects;

A, B, C, D, a_1, a_2, a_3, Q, m – constants;

$f(P)$ – porosity function.

START-3 temperature dependences of UO_2 thermal conductivity at various levels of burnup compared to results of Halden modeling [4] are shown in Figure 1.

Presented dependencies correlate up to burnup 60 MWd/kgU.

Detailed description of thermal conductivity model and its verification is presented in [5].

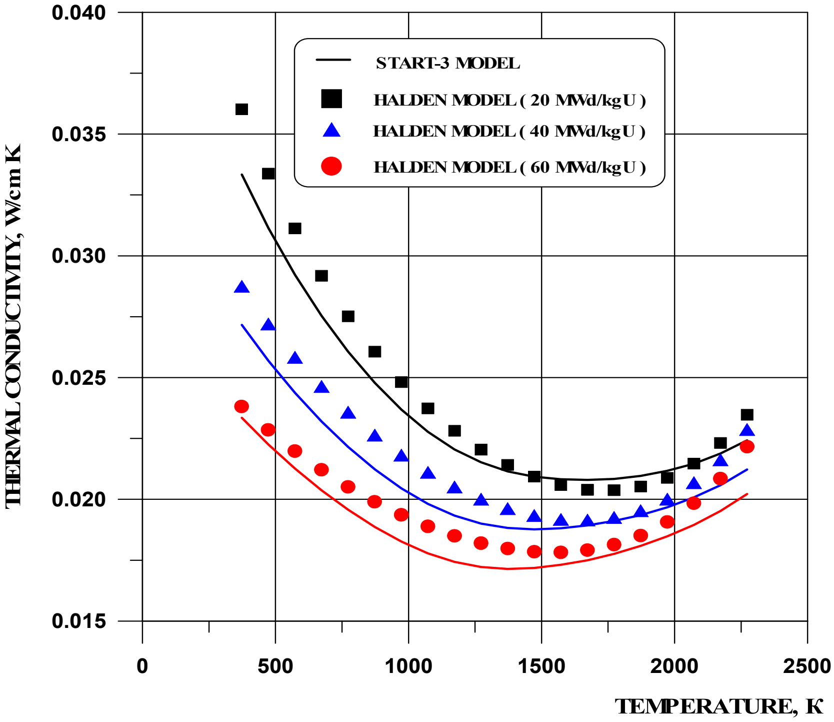

Figure 1. Temperature dependences of UO_2 thermal conductivity at various levels of burnup

Comparison of START-3 prediction and in-pile experiment values of fuel temperature obtained at SSC RIAR is shown in Figure 2. Refabricated FR of a burnup 58.4 MWd/kgU equipped with pressure transducer and thermocouple was nvestigated. Maximal calculation-experiment deviation is less than 5% (except one point). Dependence of UO_2 melting temperature on burnup used for FR reliability justification is presented in form [6]:

T_M = 2 840-0.56·B, [˚C],

where:

B – burnup, MWd/kgU.

$(U\text{-}Gd)O_2$ solidus temperature for 3.5 wt.% content of Gd_2O_3 is equal to 2550˚C, for 5 wt.% – 2450˚C [7].

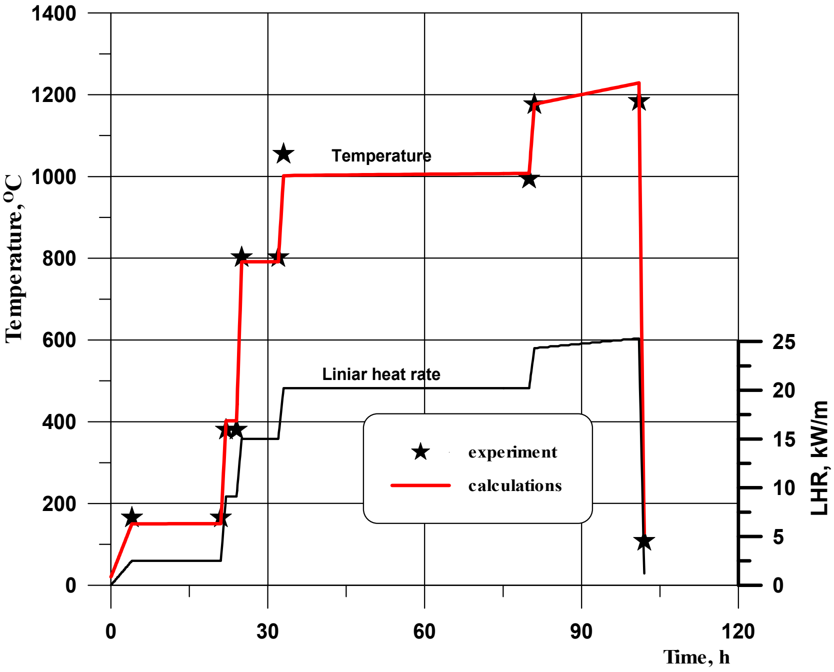

Figure 2. Comparison of calculation and experimental fuel temperature values for fuel rod of a burnup 59 MWd/kgU

3.2. Model of Gas Release and Fuel Swelling

START-3 models of FGR, fuel swelling, rim-structure formation reflect determinative influence of high burnup.

Base model solves the problem of two stage fission gas diffusion in polycrystalline fuel:

- Diffusion flow of fission gas atoms to grain boundaries;
- Subsequent quasi-diffusion percolation of fission gases via net of tunnels along grain boundaries.

Model also considers the possible release of fission gases by athermic mechanisms of “direct recoil” and “knock-out”.

Effect of high burnup is revealed in formation of peripheral rim-layer with intensive FGR.

The main reasons of FGR intensification are as follows:

- FGR from pellet periphery;
- Thermal-physical factor connected with degradation of rim-layer thermal conductivity and as a result increase of mean-volume temperature (“squaring”).

Detailed description of FGR model and its verification is presented in [8-11].

FGR model was verified up to burnup 70 MWd/kgU by full-scale computational results accounting characteristics related to rim-layer: radial profile of volume heat rate and local burnup, burnup and porosity influence upon fuel conductivity, FGR and temperature feedback, etc. (Figure 3).

Calculation of fuel swelling was verified according to experimental investigations up to burnup ≈70 MWd/kgU (Figure 4).

Calculation of fuel swelling takes account of:

- Accumulation of solid fission products in fuel matrix;

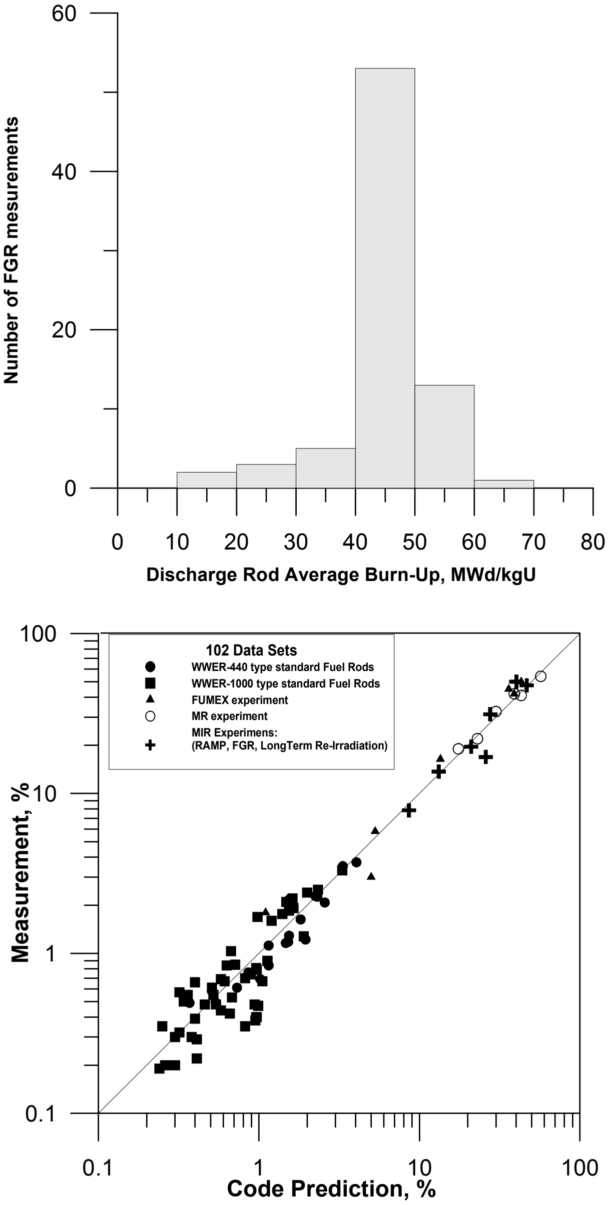

Figure 3. Verification matrix of START-3 FGR model

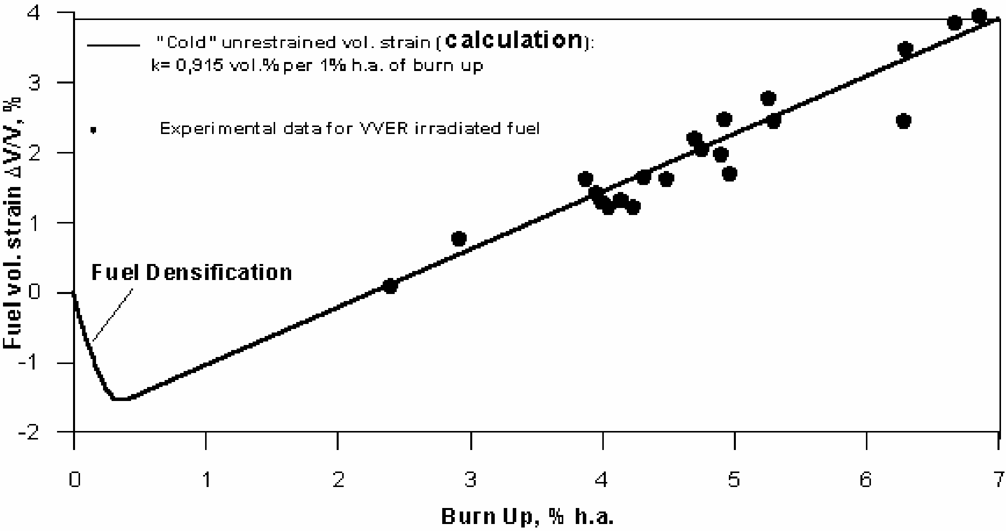

Figure 4. Swelling of fuel under low temperature irradiation

- Content of fission gas monoatoms in a grain;
- Intra- and inter-granular gas filled porosity.

4. Analysis of Thermal-Physical Characteristics of WWER Fuel Rods Under High Burnup Fuel Cycles

4.1. Analysis of Maximal Fuel Temperatures

Figures 5 and 6 show examples of maximal fuel temperature under WWER-440 (5-year fuel cycle with a portion of 6-year assemblies) and WWER-1000 (4-year fuel cycle) conditions.

Linear heat rates and burnups are applied taking account of assurance factor of their estimation.

Conservative low properties of heat transmission in fuel rod, conservative fuel rod parameters for thermo-physical analysis of maximum temperatures are chose.

Maximal temperature in WWER-440 FRs is equal 1256˚C under linear heat rate 273 W/cm, in WWER-1000 FRs – 1563˚C under linear heat rate 350 W/cm. Margin of melting is not lower than 1.8.

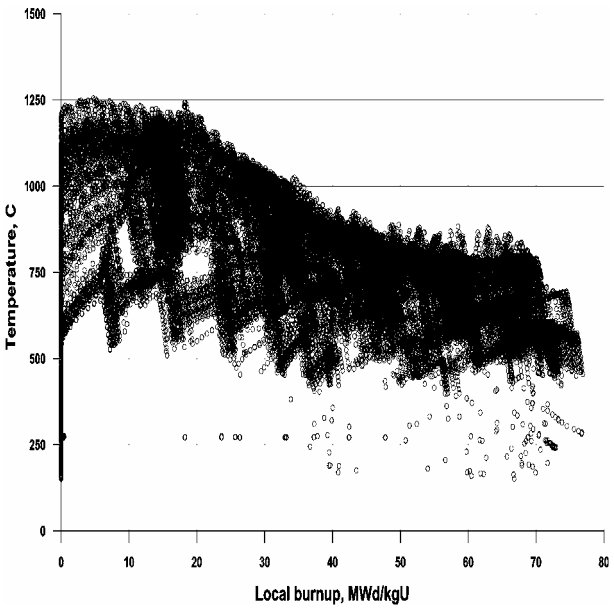

Figure 5. Maximal fuel temperatures under WWER-440 5-year cycle

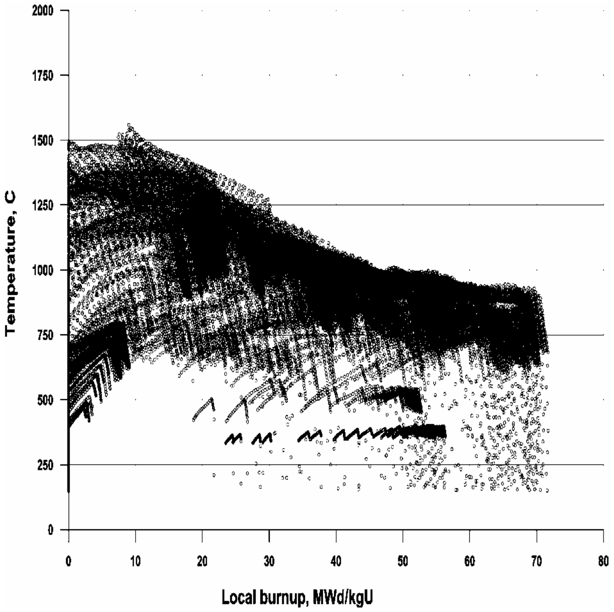

Figure 6. Maximal fuel temperatures under WWER-1000 4-year cycle

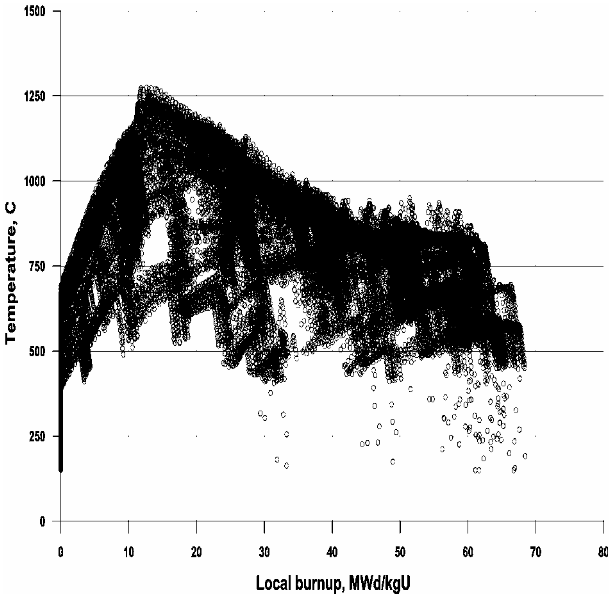

Figure 7. Maximal temperatures of (U-Gd)O$_2$ under WWER-440 5-year cycle

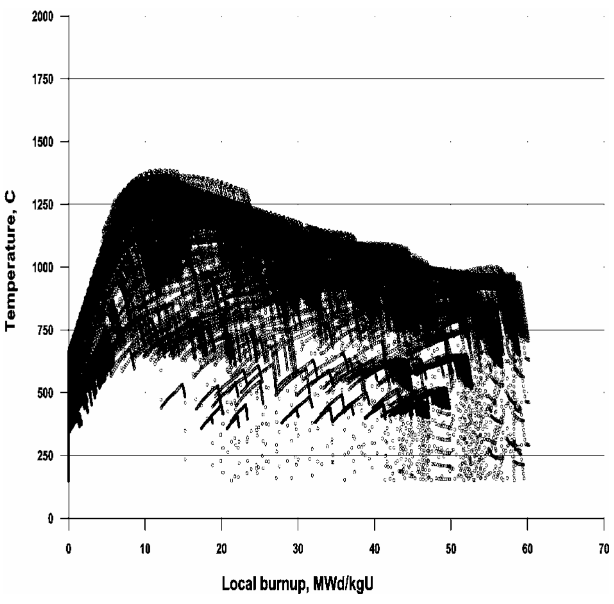

Figure 8. Maximal temperatures of (U-Gd)O$_2$ under WWER-1000 4-year cycle

Fuel temperature analysis under maximal limit heat rates 325 W/cm (WWER-440) and 448 W/cm (WWER-1000) at the initial stage of operation gave 1490˚C and 1883˚C accordingly. In this case margin of melting is ensured not lower than 1.5.

Analysis shows that margin of melting increases with increase of burnup.

Figures 7 and 8 show examples of maximal temperature of $(U\text{-}Gd)O_2$ fuel under WWER-440 (5-year fuel cycle with a portion of 6-year assemblies) and WWER-1000 (4-year fuel cycle) conditions.

Maximal temperature in WWER-440 FR(Gd)s is equal 1276˚C under linear heat rate 255 W/cm, in WWER-1000 FR(Gd)s – 1389°C under linear heat rate 274 W/cm at the beginning of the second year of operation. Margin of melting is not lower than 1.7. Thus sufficient margin of fuel melting is ensured in WWER fuel cycles of high burnup.

4.2. FGR Analysis

FGR in WWER fuel is generally determined by gas release from rim-layer since mean-volume fuel temperature is relative lower than Vitanza threshold of fuel temperature. Effects of FGR from rim-layer become apparent at burnups more than 42 MWd/kgU.

Figures 9 and 10 show examples of FGR analysis executed for WWER fuel of maximal burnup under 6-year pilot operation. Analysis was conducted accounting assurance factors of heat rate and burnup estimation at mean fuel rod parameters for FGR analysis.

Maximal FGR at the end of operation is equal 12.5% in WWER-440 FRs and 11.2% in WWER-1000 FRs. Accordingly maximum gas pressure in "hot" state is equal 7.8 MPa and 10.4 MPa. Minimum margin of limiting gas pressure ensuring not-

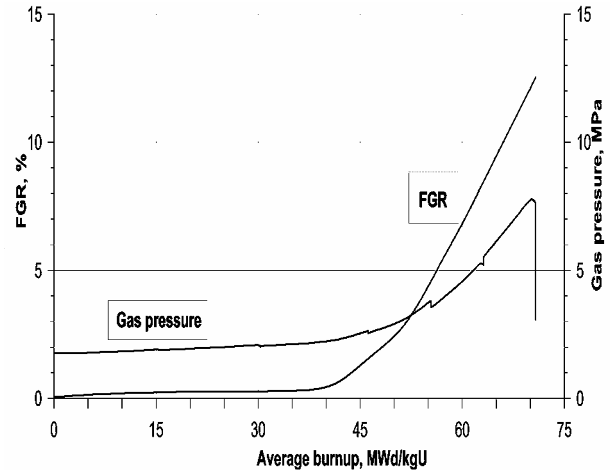

Figure 9. Maximal FGR and gas pressure in WWER-440 FR under 6-year operation

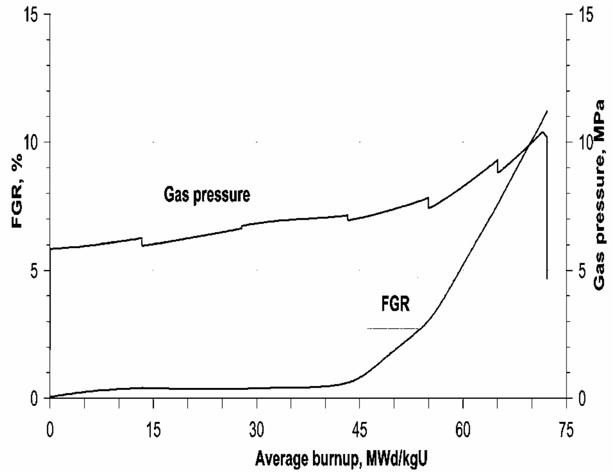

Figure 10.Maximal FGR and gas pressure in WWER-1000 FR under 6-year operation

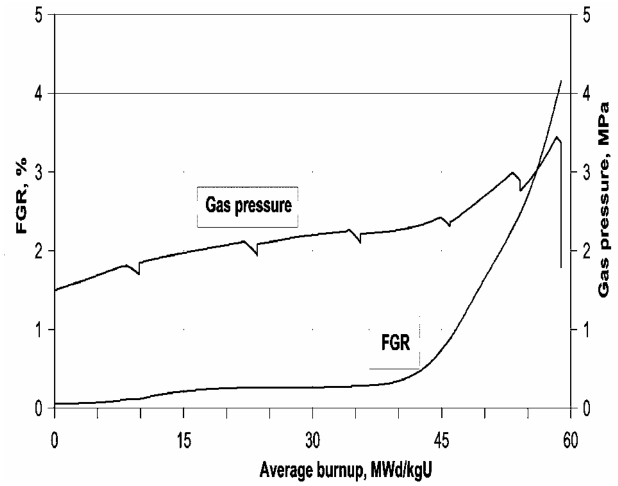

Figure 11.Maximal FGR and gas pressure in WWER-440 FR(Gd) under 6-year operation

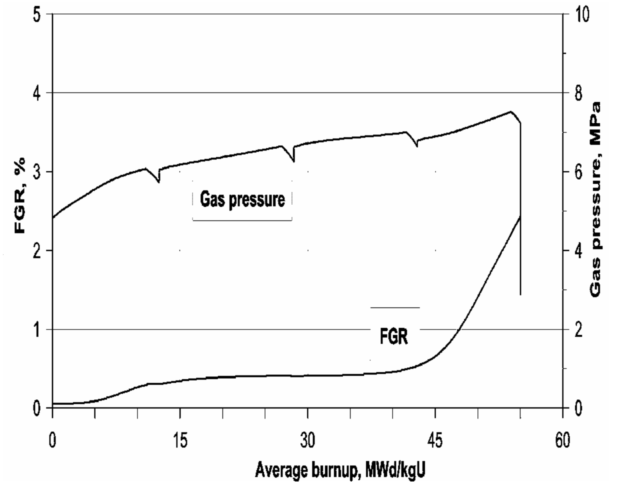

Figure 12.Maximal FGR and gas pressure in WWER-1000 FR(Gd) under 4-year operation

exceeding of coolant pressure is not lower than 1.5. Thus failure of pellet-cladding heat transfer as a result of "lift-off" effect is eliminated.

Maximal FGR at the end of operation is equal 4.15% in WWER-440 FRs(Gd) and 2.43% in WWER-1000 FRs(Gd). Accordingly maximal gas pressure in "hot" state is equal 3.44 MPa and 7.52 MPa.

Minimum margin of limiting gas pressure ensuring not-exceeding of coolant pressure is not lower than 2.1.

Thus thermal-physical criteria of FR(Gd) serviceability in cycles with uranium-gadolinium fuel are implemented with margins not lower than FR margins.

5. Mechanical Properties of Materials and FR Deformation

Mechanical properties of Zr-1%Nb alloy stabilize at flux $\approx 10^{19}$ n/cm^2 (E>0.4 MeV) and demonstrate high values of strength and plasticity at high burnups.

Mechanical properties of irradiated cladding for temperature 350-380°C:

- Ultimate strength: 340-370 MPa;
- Yield stress: 305-335 MPa;
- Total elongation: 18-24%;
- Uniform elongation: 4-6%.

Irradiation-induced growth of the alloy is stable at low level up to flux $2\cdot10^{22}$ n/cm^2 (E>0.1 MeV).

Dependencies of elongation and diameter change of WWER FRs on FA mean burnup obtained at SSC RIAR [12] are shown in Figures 13-16.

5.1. Elongation is a Linear Function of Burnup

Results of PIE of FR size parameters can be considered as an objective test of START-3 models reliability under complex stress-strain conditions and feed-backs.

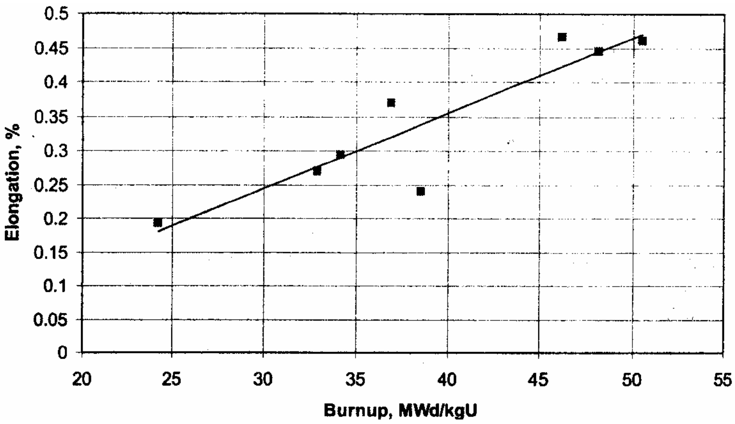

Figure 13.Elongation of FR versus mean burnup of WWER-440 FA

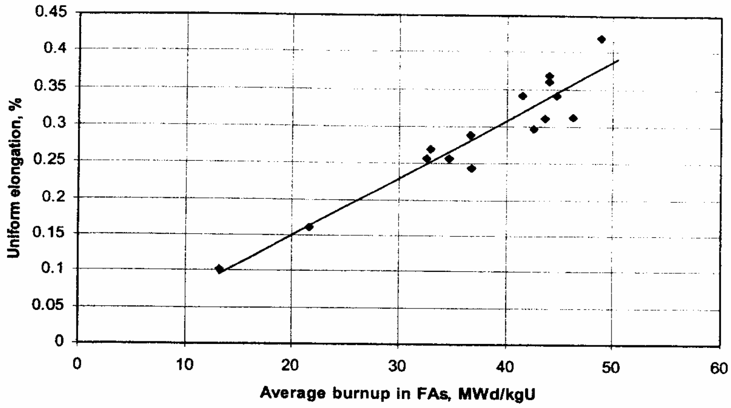

Figure 14. Elongation of FR versus mean burnup of WWER-1000 FA

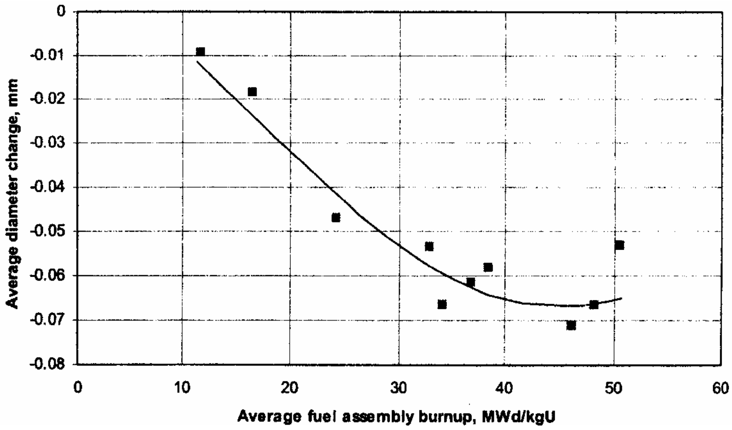

Figure 15.Change of FR diameter versus mean burnup of WWER-440 FA

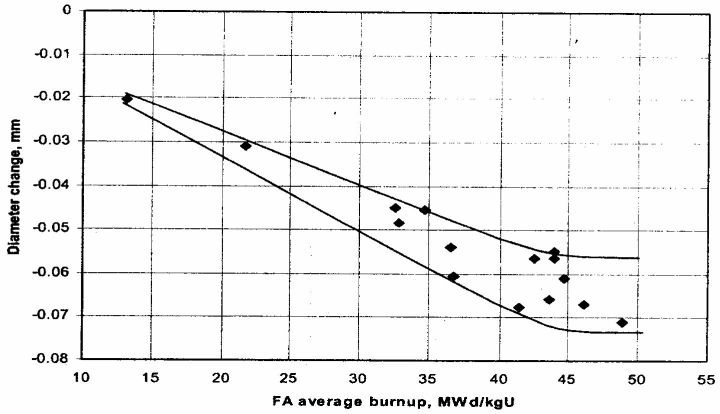

Figure 16.Change of FR diameter versus mean burnup of WWER-1000 FA

6. Computer Modelling of Strain and Strength Parameters of High-Burnup Fuel Rods

Figures 17-20 show examples of strain analysis executed for WWER FRs of maximal burnup under 6-year pilot operation. Analysis was conducted accounting assurance factors of heat rate and burnup estimation at mean fuel rod parameters for strain analysis.

Analysis shows that maximal diameter decrease of WWER-440 and WWER-1000 FRs under in-core conditions is equal 71 and 81 microns, accordingly, for a burnup 40-60 MWd/kgU. Margin of diameter decrease is not lower than 1.48. Thus reliability of FRs fixation in grids under conditions of high-burnup fuel cycles is ensured.

Hoop strain of cladding remains negative at the end of 6-year operation ensuring required conditions of heat dissipation from FR cladding.FR elongation is limited by gap between FR top plugs and FA upper nozzle.

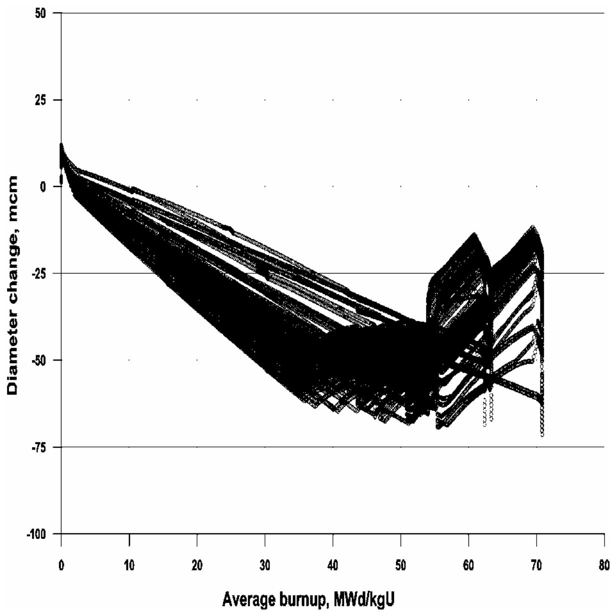

Figure 17.Diameter change of maximal burned WWER-440 FRs under 6-year operation

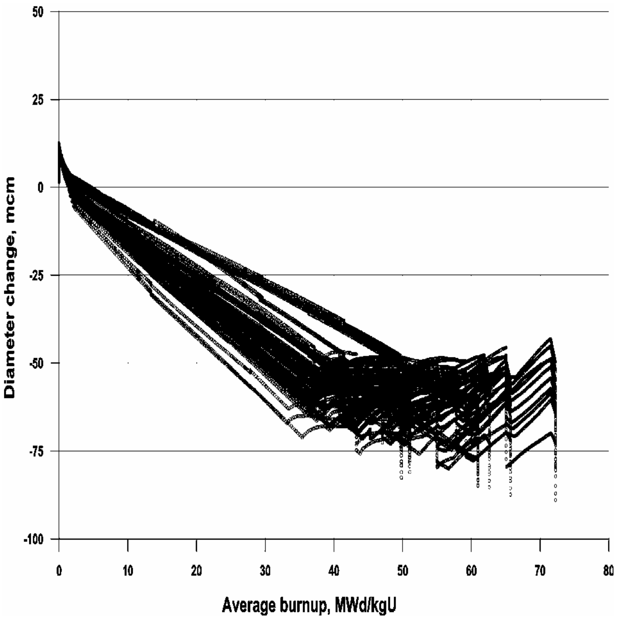

Figure 18.Diameter change of maximal burned WWER-1000 FRs under 6-year operation

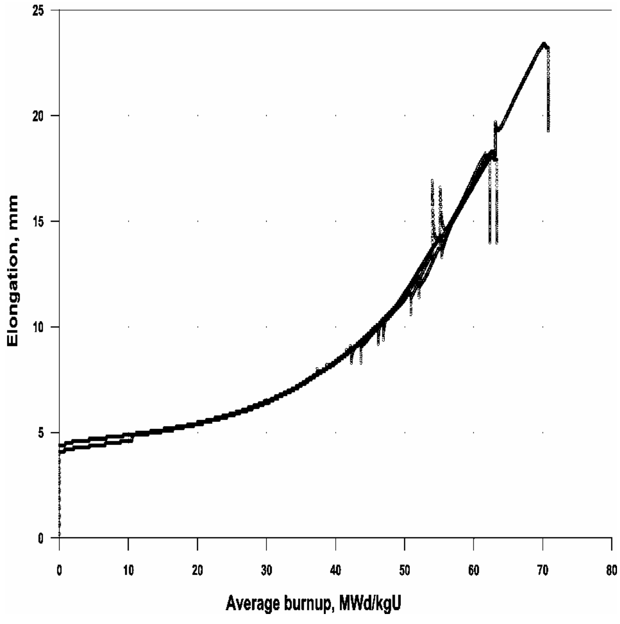

Figure 19.Elongation of WWER-440 FRs under 6-year operation

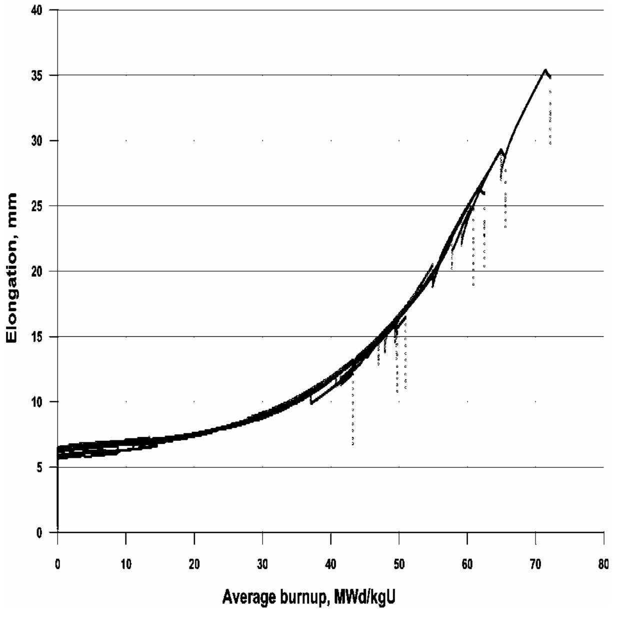

Figure 20.Elongation of WWER-1000 FRs under 6-year operation

Conservatively supposing the absence of radiation-induced growth of FA shroud it was shown that minimum “hot” gap between FR top plugs and FA upper nozzle is equal ≈6 mm and maximal “hot” elongation of FR is equal 23.4 mm under conditions of 6-year WWER-440 operation. Margin factor of FR elongation is 1.26. Maximal “cold” state elongation of FRs is 19 mm (Figure 19).

Maximal “hot” state elongation of WWER-1000 FRs is 35.4 mm under 6-year operation. Margin factor of FR elongation is 1.25. Maximal “cold” state elongation of FRs is 29.8 mm (Figure 20).

Thus analysis shows that maximal FR size changes don’t upset serviceability of WWER-440 and WWER-1000 fuel of a burnup 70 MWd/kgU.

7. Corrosion Criterion

Fulfillment of technical requirements of FR manufacturing and operation ensures absence of significant hydrogenation and oxidation of FR claddings under irradiation to high burnups.

Implementation of corrosion criteria is justified by operation experience and PIE of FR claddings

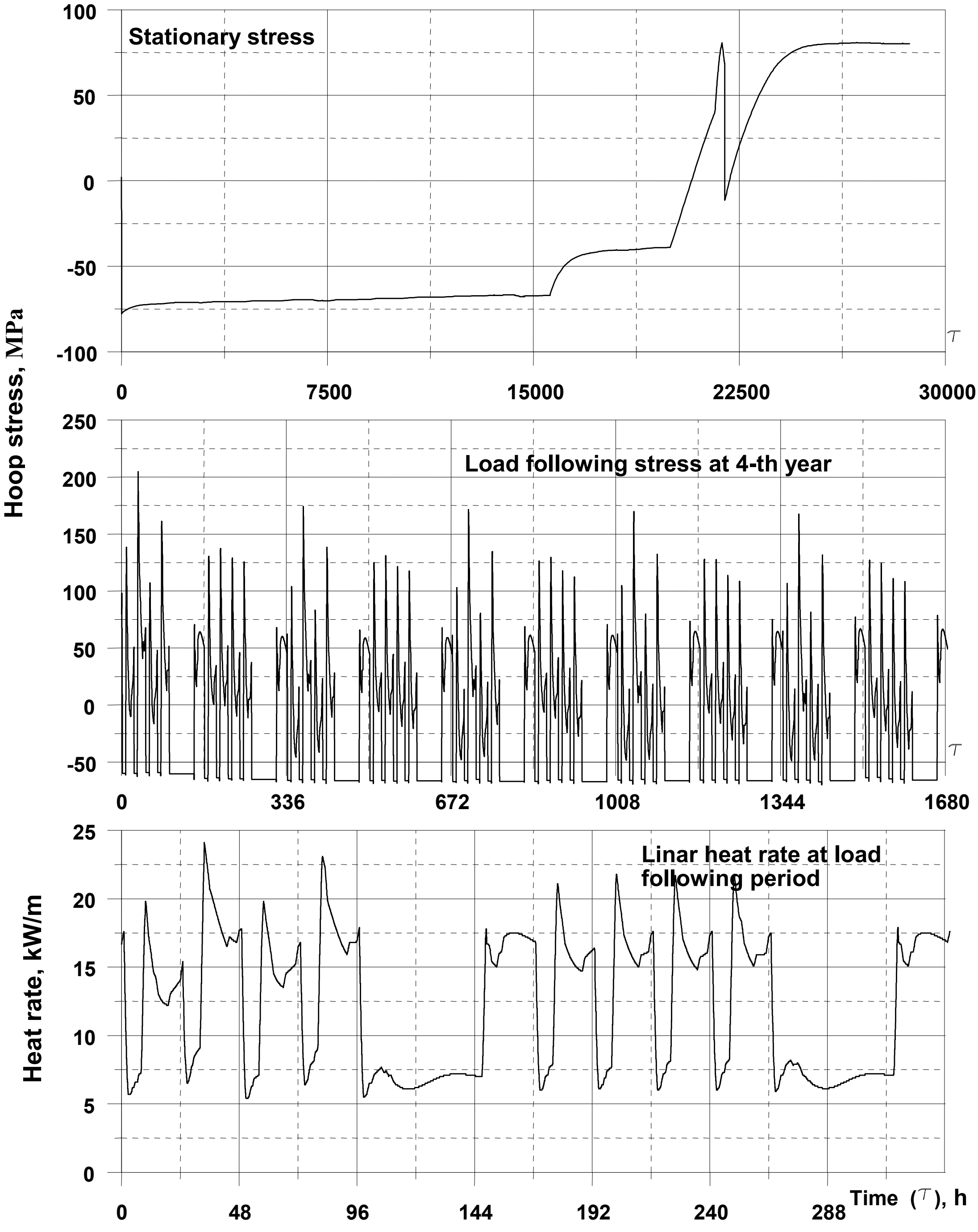

Figure 21. Hoop stress in FR cladding under tertiary regulation

irradiated up to burnup 70 MWd/kgU.

Observed corrosion of WWER FR claddings is not a factor influencing life characteristics of FR with Zr+1%Nb cladding.

Great experience of FA operation during 4-6 years justifies high corrosion stability of FR Zirconium claddings under rated coolant parameters.

PIE demonstrates that FR claddings keep high strength ($\sigma_U \geq 340$ MPa) and significant margin of plasticity ($\delta_T \geq 18\%$, $\delta_U \geq 4\text{-}6\%$).

PIE of FR claddings showed that cladding hydrogenation doesn't exceed 100 ppm with preferred tangential orientation and size of hydrides not more than 100 microns.

At given concentrations of hydrogen PIE justified absence of its effect on cladding mechanical properties.

8. Fuel Operation under Load Following Conditions

Capability of NPP operation under load following conditions is one of the main requirements of WWER fuel customers.

NPP operating schedules and requirements to work of regulation systems during load following are defined by fuel customers taking into account operation features of specific NPP units and features of national energy systems. Frequency maintenance conditions and diurnal-weekly power regulation can be considered as typical maneuvers.

Regulation systems applied to load following must on the one hand realize operation according to specified power mode during long period of campaign. Here it's taken into account that boron regulation must be minimized to decrease amount of radioactive waste. It's equivalent to maximal application of mechanical control system. On the other hand accounting the determining influence of control rod moving upon deformation of power field control systems must fulfill specific requirements of operating defined by strength parameters of FR serviceability.

Estimation of influence upon thermal-mechanical mode of fuel rods is defined by the following:

- Power changes are executed without use of control systems and only are owned to self-regulation property during network frequency changes;
- Mechanical control system is used without boron system;
- All kinds of control systems are allowed for usage.

Such requirements to control systems were assumed as a basis for division of load following levels defined for example by fuel customers for Dukovany NPP:

- Prime regulation (97.5% ±2.5%)N_{NOM};
- Secondary regulation (100%-80%-100%)N_{NOM};

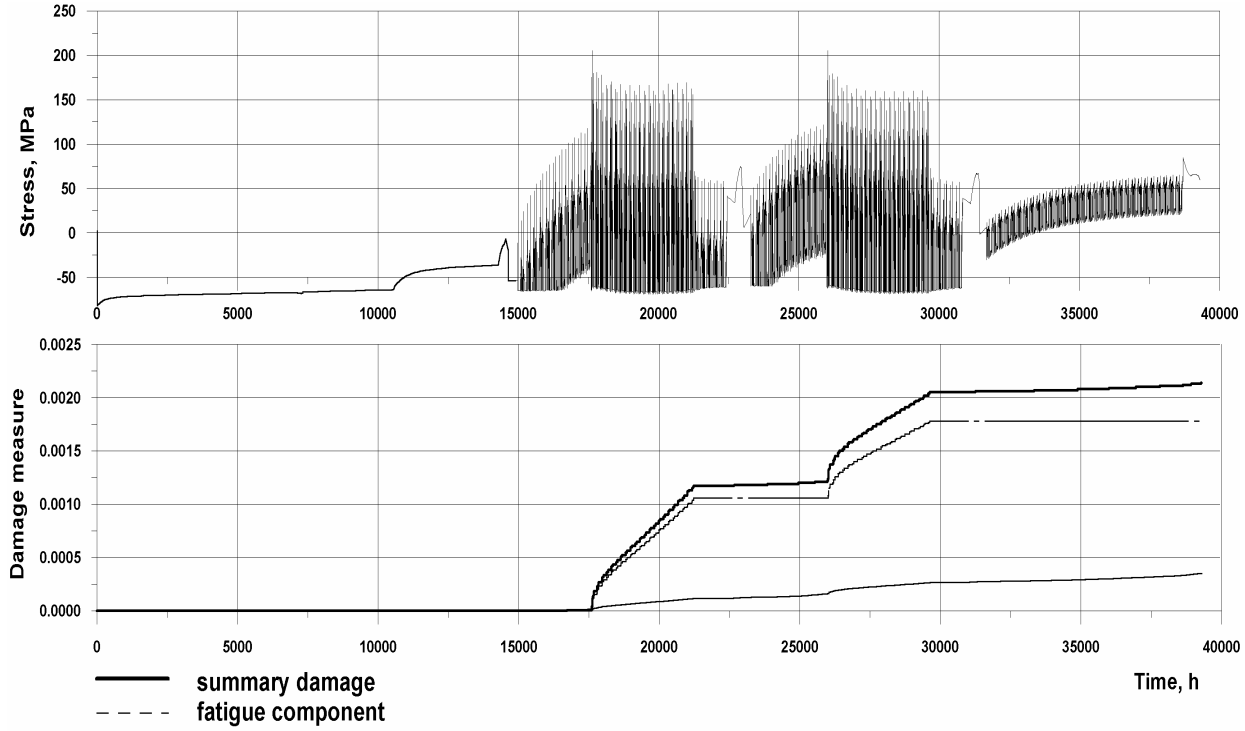

Figure 22. Analysis of damage accumulation in FR cladding under continual load following operation

- Tertiary regulation (100%-50%-100%)N_{NOM}.

Justification of FRs reliability under load following conditions is executed with START-3 code.

Main attention is focused on estimation of maximal stress in FR cladding defining FR strength. Both separate load following modes of operation and their continual application from viewpoint of long-term and fatigue strength were examined.

Some results of justification of FRs reliability under load following conditions executed for type WWER-440 Dukovany NPP are presented below.

Figure 21 shows example of FR strength analysis under the deepest tertiary regulation.

Maximal stress in FR cladding takes place under tertiary regulation at the forth year of operation. Analysis shows that maximal stresses in FR cladding reached during this mode of operation don't exceed 205 MPa and don't disturb strength criteria of FRs reliability.

Figure 22 shows results of conservative analysis of cladding damage measure during continual load following operation.

It was proposed that allowed quantity of 250 deep cycles was divided in equal parts among 3-rd and 4-th year of operation, secondary regulation was distributed uniformly over residuary part of operation.

During calculation of continual load following operation values of cladding stress and parameters of their cyclic changes were compared with relation of long-term and fatigue strength of cladding by automatic summing of accumulated static and fatigue damage.

Figure 22 shows calculated stress in FR cladding and plots of accumulated static, fatigue and total damages.

Analysis demonstrates that level of cladding stress is determined generally by moment of realization of operation mode.

Dynamic of stress changes in FR cladding reflects process of gap reduction or relaxation (depend upon moment of campaign) with tendency to achieve steady-state level depending on parameters of heat rate change.

At the first stage before the initial moment of fuel-cladding interaction damages don't practically accumulate in cladding. Damage accumulation under continual load following operation has threshold character. Total value of damage measure at the end of campaign was equal $W = 2.14 \cdot 10^{-3}$ that is substantially lower than ultimate value of damage measure $W = 1$.

Portion of damage generated by cyclic loads exceeds static damage but has value not limiting FR reliability.

Thus FR design ensure reliable operation under load following mode of 5-year fuel cycle at of Dukovany NPP Unit 2 up to FR burnup 58 MWd/kgU.

9. Conclusions

Modernization of WWER fuel cycles is carried out on the base of complete modeling and experimental justification of fuel rods up to 70 MWd/kgU.

Modeling justification of reliability of fuel rod and fuel rod with gadolinium is carried out with the use of certificated START-3 code. START-3 code has continuous experimental support.

Thermo-physical and strength reliability of WWER-440 fuel is justified for fuel rod and pellet burnups 65 MWd/kgU and 74 MWd/U, accordingly.

Results of analysis are demonstrated by the example of uranium-gadolinium fuel assemblies of second generation under 5-year cycle with a portion of 6-year assemblies and by the example of successfully completed pilot operation of 5-year cycle fuel assemblies during 6 years at unit 3 of Kolskaja NPP.

Thermo-physical and strength reliability of WWER-1000 fuel is justified for fuel rod burnup 66 MWd/kgU by the example of fuel operation under 4-year cycles and 6-year test operation of fuel assemblies at unit 1 of Kalininskaya NPP.

By the example of 5-year cycle at Dukovany NPP Unit 2 it was demonstrated that WWER fuel rod of a burnup 58 MWd/kgU ensure reliable operation under load following conditions.

Analysis has confirmed sufficient reserves of Russian fuel to implement program of JSC "TVEL" to improve technical and economical parameters of WWER fuel cycles.

References

[1] J. Rashid. Behaviour Modelling of LWR Fuel. Proceedings, 4-th International Conference WWER Fuel Performance, Modelling and Experimental Support, 1-5 October 2001, Albena Resort, Varna, Bulgaria.

[2] K. Ohira, N. Itagagaki. Thermal Conductivity Measurements at High Burnup UO_2 Pellet and a Benchmark Calculation of Fuel Center Temperature. Proceedings, International Topical Meeting LWR Fuel Performance, Portland, Oregon, 2-6 March, 1997.

[3] Owaki et al. Development of a Fuel Rod Thermal-Mechanical Analysis Code for High Burnup Fuel. IAEA Technical Committee Meeting on Nuclear Fuel Behaviour Modelling at High Burnup and its Experimental Support. 18-23 June 2000, Windermere, UK.

[4] W. Wiesenack, Assessment of UO_2 Conductivity Degradation Based on In-Pile Temperature Data. Proceedings, ANS/ENS International Topical Meeting Light Water Reactor Fuel Performance, Portland, Oregon, March 2-6, 1997, 507-511.

[5] A. Medvedev et al. Modelling of WWER Fuel Rod Temperature Condition at High Burnups in START-3 Code. Proceedings, 3-rd International Seminar WWER Fuel Performance, Modelling and Experimental Support, 4-8 October 1999, Pamporovo, Bulgaria.

[6] K. Harada et al. Melting Temperature of High Burnup UO_2 Pellet. Enlarged Halden Program Group Meeting, Lillehammer, March, 2000.

[7] V. Gorsky. Uranium-Gadolinium Oxide Fuel. P.1 – The main behaviors of Gd_2O_3 and UO_2-Gd_2O_3. Atomnaja tekhnika za rubejom, №2, 1989.

[8] Yu. Bibilashvili et al. Fission Gas Products Behavior Modelling in the START-3 Code for the WWER Fuel at High Burnup and Transient Conditions. Proceedings, 3-rd International Seminar WWER Fuel Performance, Modelling and Experimental Support, 4-8 October 1999, Pamporovo, Bulgaria.

[9] G. Khvostov et al. Modelling of RIM-Layer Features in Frames of START-3 Code Development. Proceedings, Fourth International Conference WWER Fuel Performance, Modelling and Experimental Support, 1-5 October 2001, Albena Resort, Varna, Bulgaria.

[10] Yu. Bibilashvili et al. Development of the Fission Gas Behavior Model in the START-3 Code and its Experimental Support. Proceedings, Seminar Fission Gas Behavior in Water Reactor Fuels. Cadarache, France, 26-29 September, 2000.

[11] G. Khvostov et al. The Dynamic Model of Grain Boundary Processes in High Burn-up LWR Fuel and its Application in Analysis by the START-3 Code. 5-th International Conference WWER Fuel Performance, Modeling and Experimental Support, Albena-Varna, Bulgaria, 29 September – 3 October, 2003.

[12] A. Smirnov et al. Results of Post-Irradiation Examination to Validate WWER-440 and WWER-1000 Fuel Efficiency at High Burnups. Proceedings, 4-th International Conference WWER Fuel Performance, Modelling and Experimental Support, 1-5 October 2001, Albena Resort, Varna, Bulgaria.