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International Agreement Report

Experimental Study of Narrow Pulse Effects on the Behavior of High Burnup Fuel Rods with Zr-1%Nb Cladding and UO_2 Fuel (VVER Type) under Reactivity-Initiated Accident Conditions: Test Conditions and Results

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Washington, DC 20555-0001

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Prepared for
U.S. Nuclear Regulatory Commission (United States),
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and Joint Stock Company "TVEL" (Russian Federation)

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ABSTRACT

This volume of the report contains a detailed description of calculation and test results obtained in the fast-pulse-graphite-reactor (BIGR) tests of twelve fuel rods refabricated from the VVER-440 and VVER-1000 high burnup fuel elements (50, 60 MW d/kg U).

The BIGR data base includes the following types of fuel rod characterization:

- material and geometrical parameters of VVER-440 and VVER-1000 commercial fuel elements before the base irradiation in the nuclear power plant (NPP);
- parameters of fuel cycles and characteristics of commercial fuel elements after the base irradiation;
- characteristics of twelve refabricated fuel rods before the BIGR pulse tests;
- parameters of the BIGR power pulses;
- characteristics of refabricated fuel rods during and after the BIGR tests.

FOREWORD

This two-volume report provides results of a cooperative research program involving the Russian Research Center–Kurchatov Institute, the French Institute for Radiological Protection and Nuclear Safety (IRSN), and the United States Nuclear Regulatory Commission (NRC). The research addresses the behavior of high-burnup nuclear fuel under postulated reactivity-initiated accident (RIA) conditions, based on experimental results from the Russian fast-pulse graphite reactor, known as BIGR.

The Kurchatov Institute initiated its RIA test program in 1983, several years before the accident at Chernobyl. That accident, which resulted from a rapid increase in reactivity, demonstrated that severe fuel damage may occur too quickly to be easily mitigated. However, the consequences of such an event can be reduced by thorough understanding and design.

Information concerning Russian reactivity insertion experiments in the Impulse Graphite Reactor (IGR) was first revealed to western observers in 1992. Differences between IGR and other fuel behavior tests were initially attributed to differences in Russian fuel designs and the larger pulse width of the IGR test reactor. However, the test rods used in the IGR were taken from zirconium-niobium clad uranium dioxide (UO_2) fuel rods that were commercially irradiated in pressurized, light-water-reactors. This type of cladding material is used throughout the world, and generated great interest. The IRSN and NRC recognized the value of this test program and, in 1995, joined with the Kurchatov Institute in assessing and interpreting the IGR data. Then, in July 1999, the agencies jointly published the results in a three-volume compendium, identified as NUREG/IA-0156, "Data Base on the Behavior of High Burnup Fuel Rods with Zr-1%Nb Cladding and UO_2 Fuel (VVER Type) Under Reactivity Accident Conditions."

More recently, the Kurchatov Institute addressed the issue of the broad pulse width effects in the IGR with a series of narrow pulse width experiments in the BIGR fast-pulse graphite reactor. The work was performed in cooperation with other Russian institutes and support of the Russian fuel vendor (Joint Stock Company "TVEL"). Pulses produced by the two test reactors span an extraordinary range, from 3 milliseconds in BIGR to over 700 milliseconds in IGR, and bound the expected pulse widths for postulated RIA events in commercial light-water reactors. Taken together, these test results show that cladding with very light corrosion is remarkably resistant to failure — even under high-burnup conditions.

Results of the BIGR program, as documented in this report, demonstrate the continued value of the cooperative efforts of the Kurchatov Institute, the IRSN, and the NRC. This collaborative program further allows a comparison of conclusions from other data sources (e.g., France, Japan, and the U.S.). By comparing these results, studying the employed techniques, and creating a common language necessary for the mutual understanding these events, it will be possible to establish more appropriate regulatory limits for reactivity-initiated accidents.

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U.S. Nuclear Regulatory
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- V. Sazhnov (Russian Federal Nuclear Centre "All-Russian Research Institute of Experimental Physics:): the performance of the BIGR tests with VVER refabricated fuel rods;
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- G. Maslov, V. Ilyin (Russian Federal Nuclear Centre "All-Russian Research Institute of Experimental Physics"): experimental measurements and computer calculations of neutronic parameters during the BIGR tests;
- A. Shestopalov (Nuclear Safety Institute of Russian Research Centre "Kurchatov Institute"): FRAP-T6/VVER calculations of thermal mechanical parameters of high burnup fuel rods under the BIGR test conditions;
- E. Zvir, L. Stupina, A. Svyatkin (State Research Centre "Research Institute of Atomic Reactors"): pre-test and post-test examinations of refabricated fuel rods including metallographic studies and computer processing of obtained data;
- A. Chetvyarikov (State Research Centre "Research Institute of Atomic Reactors"): the management by radio chemical measurements of the fuel isotopic composition;
- A. Konobeev, G. Abyshov (Nuclear Safety Institute of Russian Research Centre "Kurchatov Institute"): the computer processing of some experimental data.

Without the efforts of these individuals, and their willingness to share results of several special investigations, this report would not have been possible.

1. EXECUTIVE SUMMARY

Taking into account that the BIGR[a] tests were performed under reactivity-initiated-accident (RIA) conditions to widen the VVER[b] RIA high burnup fuel data base obtained earlier due to the pulse graphite reactor (IGR[c]) tests, it was decided to keep approximately the same format of the test data organization, which was developed during the preparation of the IGR/RIA data base [1]. In accordance with this approach, the Volume 2 of the BIGR report contains several types of test data listed in Fig. 1. As it can be observed from this Figure, the high burnup fuel rods tested in the BIGR reactor were refabricated from the VVER-440 and VVER-1000 fuel elements irradiated at the NovoVoronezh and Kola nuclear power plants (NV[d] NPP and Kola[e] NPP). To follow the evolution of the cladding and fuel changes from the beginning of fuel cycles at the NPP to RIA accident conditions at the burnup 50, 60 MW d/kg U, special measurements of fuel rod parameters were performed and presented in several Appendices of this volume of the report. The contents of each Appendix are given in Chapter 2 of this volume.

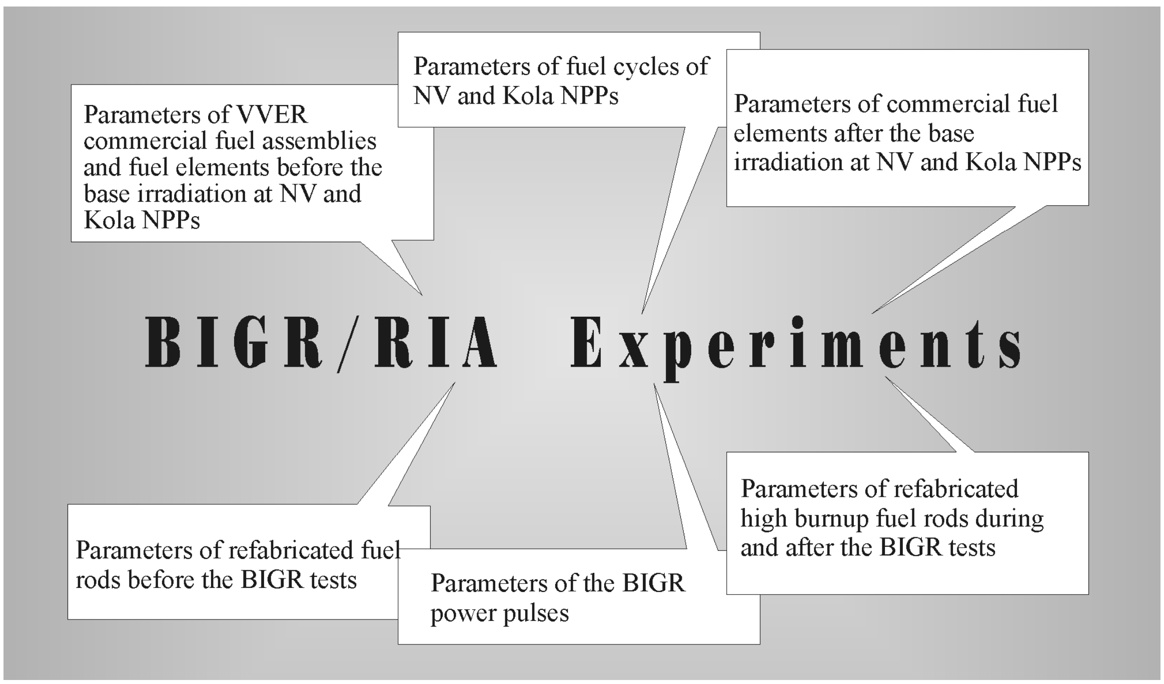


Fig. 1. Arrangement of the BIGR/RIA test results

[a] BIGR – Bystry Impulsny Graphitovy Reactor (Fast Pulse Graphite Reactor)

[b] VVER – Vodo-Vodyanoy Energetichesky Reactor (Russian type of Pressurized Water Reactor)

[c] IGR – Impulsny Graphitovy Reactor (Pulse Graphite Reactor)

[d] NV – Novovoronezhskay (Nuclear Power Plant)

[e] Kola – Kolskay (Nuclear Power Plant)

REFERENCES

[1] Yegorova L., Asmolov V., Abyshov G., Malofeev V., Avvakumov A., Kaplar E., Lioutov K., Shestopalov A., Bortash A., Maiorov L., Mikitiouk K., Polvanov V., Smirnov V., Goryachev A., Prokhorov V., and Vurim A. “Data Base on the Behavior of High Burnup Fuel Rods with Zr-1%Nb Cladding and UO_2 Fuel (VVER Type) under Reactivity Accident Conditions”, RRC "Kurchatov Institute" report NSI RRC 2179, Vol.1-3, 1999 (also USNRC report NUREG/IA-0156 and IPSN report IPSN 99/08–2).

2. GUIDE TO THE DATA BASE

The BIGR/RIA data base is subdivided into five subject sets of data presented in the following Appendices:

Appendix A	Reference Characteristics of VVER-440 and VVER-1000 Commercial Fuel Elements before the Base Irradiation
Appendix B	Fuel Cycle Parameters and Post-Irradiation Characteristics of Commercial Fuel Rods
Appendix C	Characteristics of Refabricated Fuel Rods before the BIGR Tests
Appendix D	Characteristics of the BIGR Power Pulses
Appendix E	Characteristics of Refabricated Fuel Rods after the BIGR Tests

The subsections of this Chapter contain some important comments, which may simplify the work with this data base.

2.1. Comments to Appendix A

In this Appendix reference parameters of three fuel assemblies of the VVER-440 and VVER-1000 types are presented. The most part of these parameters was determined with using the standard documentation of the manufacturer. As for differences in characteristics of these assemblies at the beginning of the base irradiation, the following parameters may be pointed out:

- the initial fill gas pressure in VVER-440 fuel elements (Helium, 0.5–0.7 MPa)[a] is lesser significantly than that in VVER-1000 fuel elements (Helium, 1.9–2.6 MPa)[a];
- each of these three fuel assemblies had fuel elements with a central hole, but of a different diameter fuel pellet (1.2, 1.6–1.7, 2.4 mm);
- two types of fuel pellets were used in these fuel assemblies:
    - simple cylindrical pellets;
    - cylindrical pellets with chamfers.

2.2. Comments to Appendix B

This Appendix contains two types of the data:

1. The data characterizing fuel cycles of six fuel elements, which were used for the manufacturing of twelve refabricated fuel rods tested in the BIGR reactor.
2. The data characterizing parameters of these six fuel elements in accordance with the post-irradiation-examination (PIE) results.

The first type of the data allowed to perform neutronic calculations of base irradiation histories for these fuel elements. Due to these calculations, radial and axial distributions of the isotopic composition of high burnup fuel was determined in the each fuel element.

The second type of the data characterizes the microstructure of fuel and cladding for six fuel elements, the fission gas release (FGR) at the end of irradiation, fuel burnup, hydrogen content in the irradiated cladding and geometrical sizes of high burnup fuel and irradiated cladding. The analysis of these data allowed to reveal the following important features:

- four fuel elements of the VVER-1000 type had approximately the similar maximum burnup (47.8–50.12 MW d/kg U), geometrical parameters of fuel and cladding, cladding hydrogen content ($5 \cdot 10^{-3}$ % by volume), rim layer thickness (0.05–0.07 mm) and residual value of fuel/cladding gap (0.017–0.032 mm);
- two fuel elements of the VVER-440 type had the similar maximum burnup also (61.6 and 61.7 MW d/kg U). Unfortunately, it was impossible to compare the most part of other characteristics for these fuel elements because the PIE data of one of these elements were very limited;
- nevertheless, the comparison of parameters of fuel elements on two levels of the maximum fuel burnup (47.8–50.12 and 61.6–61.7 MW d/kg U correspondently) allowed to reveal that:

---

[a] This parameter is presented at the room temperature

- the rim layer thickness was increased from 50–70 μm at 50 MW d/kg U up to 150–200 μm at 62 MW d/kg U burnup;
- a radial fuel/cladding gap was not apparent at 62 MW d/kg U burnup;
- the hydrogen content in the irradiated cladding was somewhat increased at 62 MW d/kg U burnup. This fact correlates with the data presented in Table C.1 of Appendix C to characterize the cladding oxidation after the base irradiation. These data showed that at 50 MW d/kg U burnup, the irradiated cladding was covered with the 3–5 μm zirconium dioxide layer on the outer surface only. At 62 MW d/kg U burnup, the oxidation of the cladding internal surface was observed. The thickness of inner ZrO_2 layer was 8–10 μm although the outer oxide layer remained 3–5 μm.

2.3. Comments to Appendix C

This Appendix is devoted to the presentation of measured and calculated parameters of twelve refabricated fuel rods before the BIGR tests. The individual characterization of each fuel rod is contained in Appendices C-1 – C-12. Besides, the reference and average representative values of parameters are listed in Tables C.1–C.3 of Appendix C. Design schemes of refabricated fuel rods supplement this data base.

Individual characteristics of fuel rods presented in Appendices C-1 – C-12 include the following graphical and tabular data:

- radial distribution of isotopic nuclear concentrations in four radial fuel layers;
- axial distributions of the cladding average outer diameter, fuel mass, gas flow area, burnup, intensity of Cs and Eu isotopes and results of the eddy current examination.

General differences between initial parameters of these fuel rods were as follows:

- eight fuel rods had burnup in the range 46.9–48.6 MW d/kg U and four fuel rods had the burnup in the range 59.8–60.5 MW d/kg U;
- ten fuel rods had the initial fill gas pressure in the range 2.0–2.1 MPa and two fuel rods had the initial fill gas pressure 0.1 MPa;
- the fuel stack in one fuel rod (#RT3) was damaged at the refabrication. The obtained fuel configuration (along the axis) is presented in the data base.

2.4. Comments to Appendix D

This Appendix consists of the following data characterizing the BIGR pulse conditions:

- the BIGR power history at the test of each fuel rod;
- pulse half-width for the BIGR tests of twelve fuel rods.

The BIGR power histories presented in this Appendix have the status of the as-measured parameter. This data base was developed in accordance with the neutron detector recording. The procedure of these experimental data transformation into the input data for the computer codes is described in the Volume 1 of the report.

2.5. Comments to Appendix E

This appendix consists of twelve subappendices with the following types of data:

- appearance of the fuel rod and photographs of fuel and cladding microstructure obtained in the PIE procedures;
- time dependent energy characteristics of the fuel rod during the BIGR test (power, number of fissions, energy deposition, fuel enthalpy). It should be noted that two independent procedures were used to determine neutronic parameters of the fuel rod versus time and the fuel enthalpy versus time. In the first case, these two procedures were developed in the Russian Research Centre “Kurchatov Institute” (RRC KI) and Russian Federal Nuclear Centre “All-Russian Research Institute of Experimental Physics” (VNIIEF) (see volume 1 of the report).

In the second case, two different codes (FRAP-T6/VVER and RAPTA-5) were used in the RRC KI and A.A. Bochvar All-Russian Research Institute of Inorganic Materials (VNIINM) to calculate the fuel enthalpy (see volume 1 of the report). Taking into account that results of neutronic calculations performed in accordance with RRC KI and VNIIEF procedures are very similar, the tabular data contain the average values only. The RRC KI and

VNIINM data characterizing the fuel enthalpy are similar in general. But to compare definite differences in these data, results of both calculations are presented in the report:

- to illustrate the specific character of the energy deposition radial distribution in the high burnup fuel, the tabular and graphical data were incorporated into the data base. In addition to these data, the transformation of the fuel enthalpy radial profile as a function of time is presented also in accordance with the FRAP-T6/VVER and RAPTA-5 calculations;
- the interpretation of the fuel rod thermal mechanical behavior during the BIGR test is presented in accordance with results of FRAP-T6/VVER and RAPTA-5 calculations;
- PIE results characterizing the cladding and fuel strain, cladding oxidation and FGR are listed in the graphical and tabular forms. Appendix A–13 contains the data base characterizing the azimuthal distribution of cladding thickness in fuel rods ## RT7–12 obtained duel to the processing of cross-section images;
- the last position of each subappendix contains the major results of the BIGR test in accordance with the calculated and experimental data.

To overcome the difficulties with terminology used in this Appendix, a special glossary is presented in Table 2.1.

Table 2.1. The glossary of neutronics and energy parameters presented in Appendix E

	Term	Meaning of term
1.	Relative reactor power vs. time (per-unit)	The reactor power in the place of the VVER fuel rod installation determined in accordance with the procedure presented in Volume 1 of the report
2.	Cumulative number of fissions in the fuel rod vs. time (fiss.)	A total number of fissions occurred within the whole fuel mass by the i-time
3.	Power of fuel rod vs. time (kW)	Power generated in the total mass of fuel due to the whole set of fissile isotopes by the i-time
4.	Energy deposition in the fuel rod vs. time (cal/g fuel)	Energy generated in the whole fuel mass by i-time and normalized for the fuel mass
5.	Number of fissions vs. radial fuel layer (fiss.)	A total number of fissions occurred in the undamaged part of a given radial layer of the fuel column within 0–∞ s
6.	Power vs. radial fuel layer (kW)	The maximum power noted during the BIGR test in the radial fuel layer
7.	Energy deposition vs. radial fuel layer (cal/g fuel)	Total energy deposition generated in a given radial layer normalized for the fuel mass within time interval 0–∞ s
8.	Energy deposition vs. radial fuel layer (per-unit)	Energy deposition of a given radial layer of the fuel column normalized for energy deposition in the 4^{th} radial layer
9.	Fuel enthalpy vs. time (cal/g fuel)	Radially averaged fuel enthalpy versus time for any cross-section (the axial peak power factor is 1)

APPENDIX A

REFERENCE CHARACTERISTICS OF VVER-440 AND VVER-1000 COMMERCIAL FUEL ELEMENTS BEFORE THE BASE IRRADIATION

Table A.1. Reference characteristics of VVER commercial fuel element before the irradiation

Characteristic	Unit	Value		
Fuel assembly type	–	VVER-440	VVER-1000	VVER-440
Commercial number of fuel assembly	–	14422222	ED4108	23635228
1. UO_2 fuel				
1.1. Isotopic composition				
U^{235}	% by weight	4.37[*]	4.40	3.60
U^{238}	% by weight	95.57	95.54	–
U^{234}	% by weight	0.03	0.03	–
U^{236}	% by weight	0.03[*]	0.03	–
1.2. Enrichment	%	4.37[*]	4.40	3.60
1.3. Oxygen-to-metal ratio	per-unit	2.001–2.002[*]	2.000–2.015	–
1.4. Density	g/cm^3	10.5–10.7[*]	10.5–10.8	10.4–10.8
1.5. Grain size	µm	6.6[*]	4–8	–
1.6. Pellet shape	–	without chamfers	without chamfers	with chamfers
1.7. Pellet outer diameter	mm	7.54–7.58[*]	$7.57_{-0.04}$	$7.60_{-0.07}$
1.8. Diameter of central hole	mm	1.6–1.7[*]	2.4±0.05	$1.20^{+0.8}$
1.9. Pellet height	mm	8–14	9–14	11±3
1.10. Fuel mass	g	1087±22	1469±22	1041±21
2. Zr-1%Nb cladding				
2.1. Composition:				
Zr	% by weight	98.67–98.87	98.67–98.87	98.67–98.87
Nb	% by weight	0.9–1.1	0.9–1.1	0.9–1.1
O_2	% by weight	< 0.1	< 0.1	< 0.1
N, C, Si, Al, Mo, Ni, Fe	% by weight	< 0.13	< 0.13	< 0.13
2.2. Outer diameter	mm	$9.1^{+0.1}_{-0.05}$	$9.13^{+0.06}_{-0.05}$	$9.1^{+0.1}_{-0.05}$
2.3. Inner diameter	mm	$7.72^{+0.08}$	$7.72^{+0.08}$	$7.72^{+0.08}$
3. Fuel rod				
3.1. Design	–	See Fig. A.1	See Fig. A.2	See Fig. A.3
3.2. Upper plenum length	m	$85^{+8.0}_{-9.0}$	$239^{+21.0}_{-4.0}$	–
3.3. Fuel stack length	mm	2420^{+10}_{-10}	3530^{+4}_{-12}	2320^{+10}_{-10}
3.4. Gas pressure[**]	MPa	0.5–0.7	1.9–2.6	0.5–0.7
3.5. Gas composition	–	He	He	He
3.6. Internal void volume	cm^3	13.7	14.5	38.3
3.7. Pitch[***]	mm	12.2	12.75	12.2
3.8. Hydraulic diameter	mm	8.93	10.5	8.93

[*] These values were measured during the fabrication. Other values were determined from specifications of fuel rods

[**] At the room temperature

[***] The distance between the centers of 2 adjacent rods in the VVER hexagonal geometry

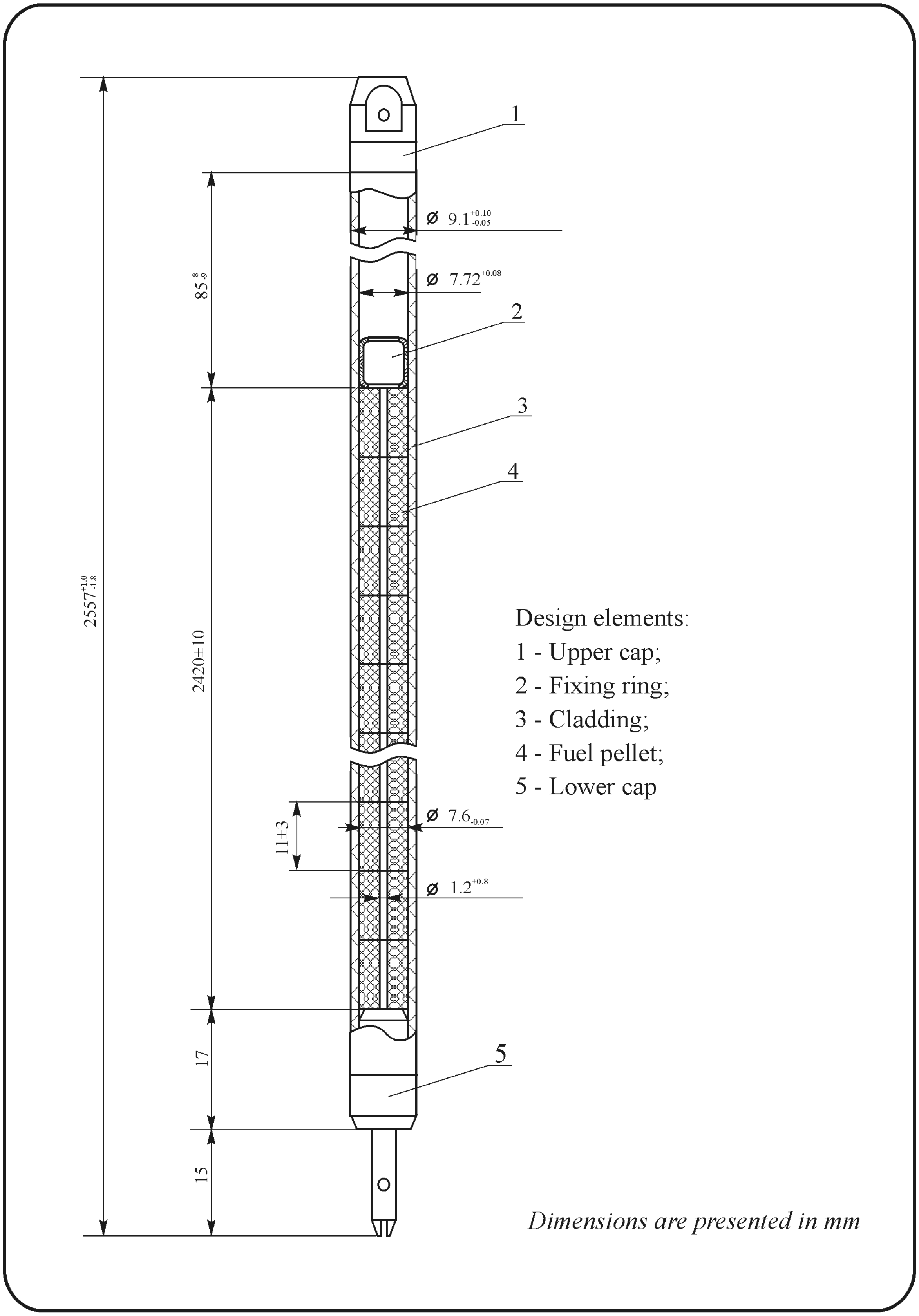
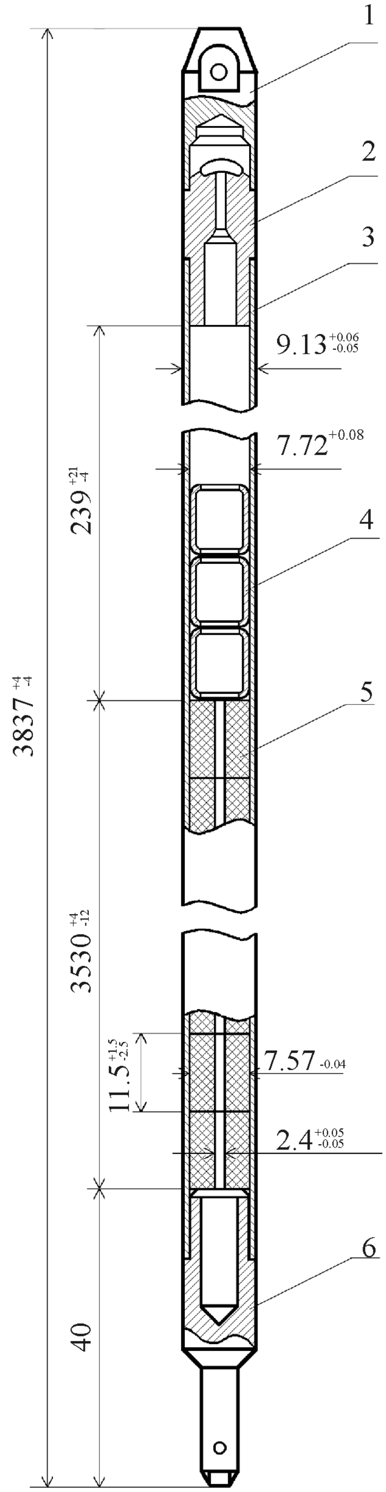


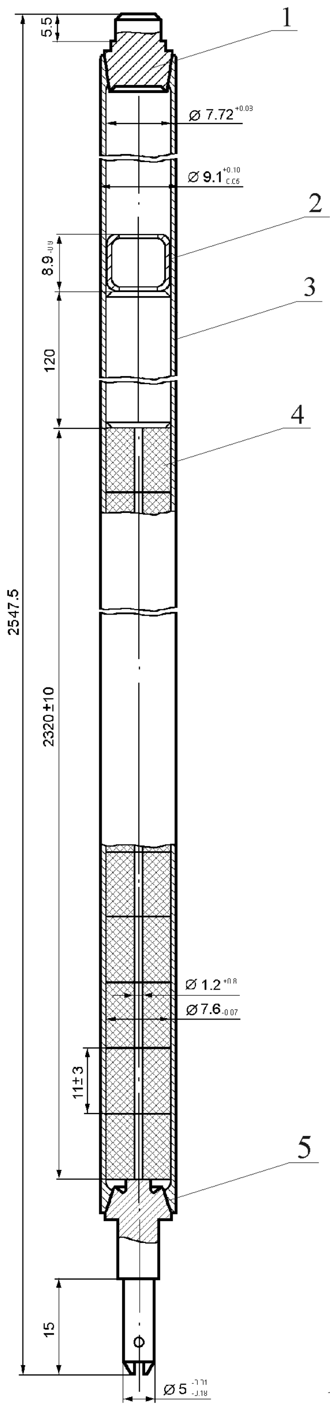
Fig. A.1. Design scheme of VVER-440 commercial fuel rod from the fuel assembly #14422222



Design elements:
1 - Upper cap;
2 - Plug;
3 - Cladding;
4 - Fixing ring;
5 - Fuel pellet;
6 - Lower cap

Dimensions are presented in mm

Fig. A.2. Design scheme of VVER-1000 commercial fuel rod from the fuel assembly #ED4108



Design elements:
1 - Upper cap;
2 - Fixing ring;
3 - Cladding;
4 - Fuel pellet;
5 - Lower cap

Dimensions are presented in mm

Fig. A.3. Design scheme of VVER-440 commercial fuel rod from the fuel assembly #23635228

APPENDIX B

FUEL CYCLE PARAMETERS AND POST-IRRADIATION CHARACTERISTICS OF COMMERCIAL FUEL RODS

Table B.1. Base irradiation history of fuel assembly #14422222

Characteristic	Unit	Value
1. Number of fuel assembly	–	14422222
2. Operation place	–	3rd unit of Kola NPP
3. Number of cycles	–	5
4. Operation periods	ef.day	245.6; 336.0; 298.5; 379.7; 305.5[a]
5. Irradiation beginning	–	24.09.86
6. Irradiation end	–	15.10.91
7. Reactor thermal power	MW	1375
8. Fuel assembly location in the reactor for each fuel cycle	–	See Fig. B.1.
9. The arrangement of fuel rods in the fuel assembly	–	See Fig. B.2
10. Boric acid concentration for each fuel cycle	g/kg	5.95; 6.84; 6.71; 7.38; 5.26
11. Inlet coolant temperature	C	268
12. Outlet coolant temperature	C	298
13. Coolant pressure	MPa	12.8
14. Mass flow rate	kg/m^2s	4000
15. Power history[b]	–	see Table B.6

Table B.2. Base irradiation history of fuel assembly #ED4108

Characteristic	Unit	Value
1. Number of fuel assembly	–	ED4108
2. Operation place	–	5th unit of NovoVoronezh NPP
3. Number of cycles	–	3
4. Operation periods	ef.day	301.7; 261.7; 317.8[a]
5. Irradiation beginning	–	05.06.86
6. Irradiation end	–	11.07.90
7. Reactor thermal power	MW	3000
8. Fuel assembly location in the reactor for each fuel cycle	–	See Fig. B.3
9. The arrangement of fuel rods in the fuel assembly	–	See Fig. B.4
10. Boric acid concentration for each fuel cycle	g/kg	6.33; 6.33; 7.15
11. Inlet coolant temperature	C	287
12. Outlet coolant temperature	C	317
13. Coolant pressure	MPa	15.7
14. Mass flow rate	kg/m^2s	5000
15. Power history	–	see Table B.5

[a] It is the list of durations for each fuel cycle (ef.day)
[b] see comments to Table B.3

Table B.3. Base irradiation history of fuel assembly #23635228

Characteristic	Unit	Value
1. Number of fuel assembly	–	23635228
2. Operation place	–	4th unit of NovoVoronezh NPP
3. Number of cycles	–	5
4. Operation periods	ef.day	98.7; 325.1; 372.1; 350.7; 368.1[a]
5. Irradiation beginning	–	17.01.90
6. Irradiation end	–	15.02.97
7. Reactor thermal power	MW	–[bb]
8. Fuel assembly location in the reactor for each fuel cycle	–	See Fig. B.5
9. The arrangement of fuel rods in the fuel assembly	–	See Fig. B.6
10. Boric acid concentration for each fuel cycle	g/kg	–[b]
11. Inlet coolant temperature	C	–[b]
12. Outlet coolant temperature	C	–[b]
13. Coolant pressure	MPa	–[b]
14. Mass flow rate	kg/m^2s	–[b]
15. Power history [c]	–	–[b]

[a] It is the list of durations for each fuel cycle (ef.day)
[b] The data were not open to this research
[c] The VVER-440 reactor contains two types of fuel assemblies, operating assemblies and follower (control) assemblies. Assembly #228, from which refabricated rod #RT7 was taken, is the follower type. Therefore, the design of the appropriate fuel elements differs from the design of the operating fuel element (#222), from which other refrabricated rods were taken. The follower assemblies are the part of the reactor control system. In the general case, the follower assemblies are not in the core with their full length. Their positions can change during the operation of the unit. Therefore, the characterization of the power history for such an assembly is a very difficult task and the linear heat rating for refrabricated rod #RT7 is not presented in appropriate Table.

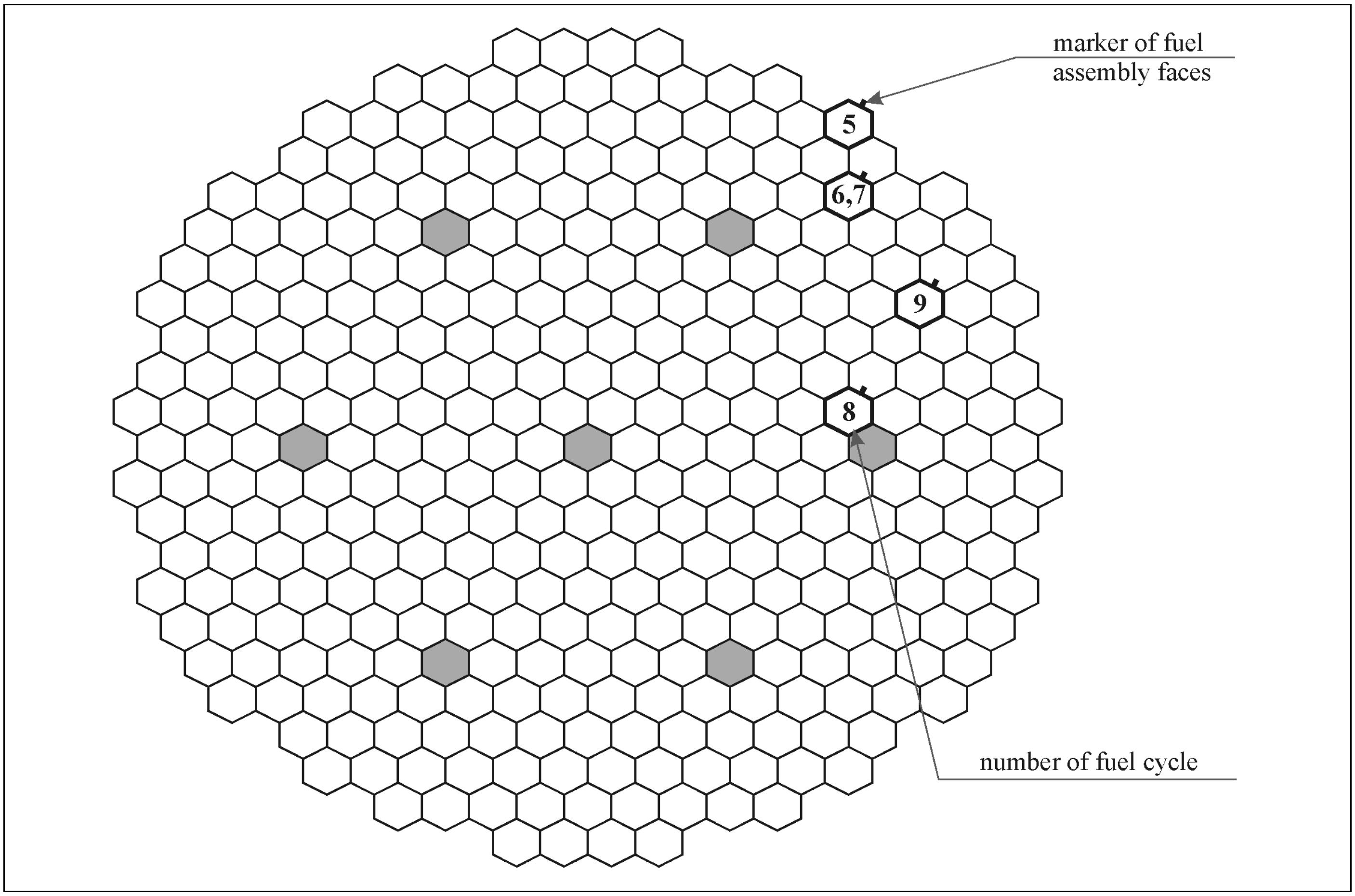


Fig. B.1. Arrangement of fuel assembly #14422222 (222) in the reactor core

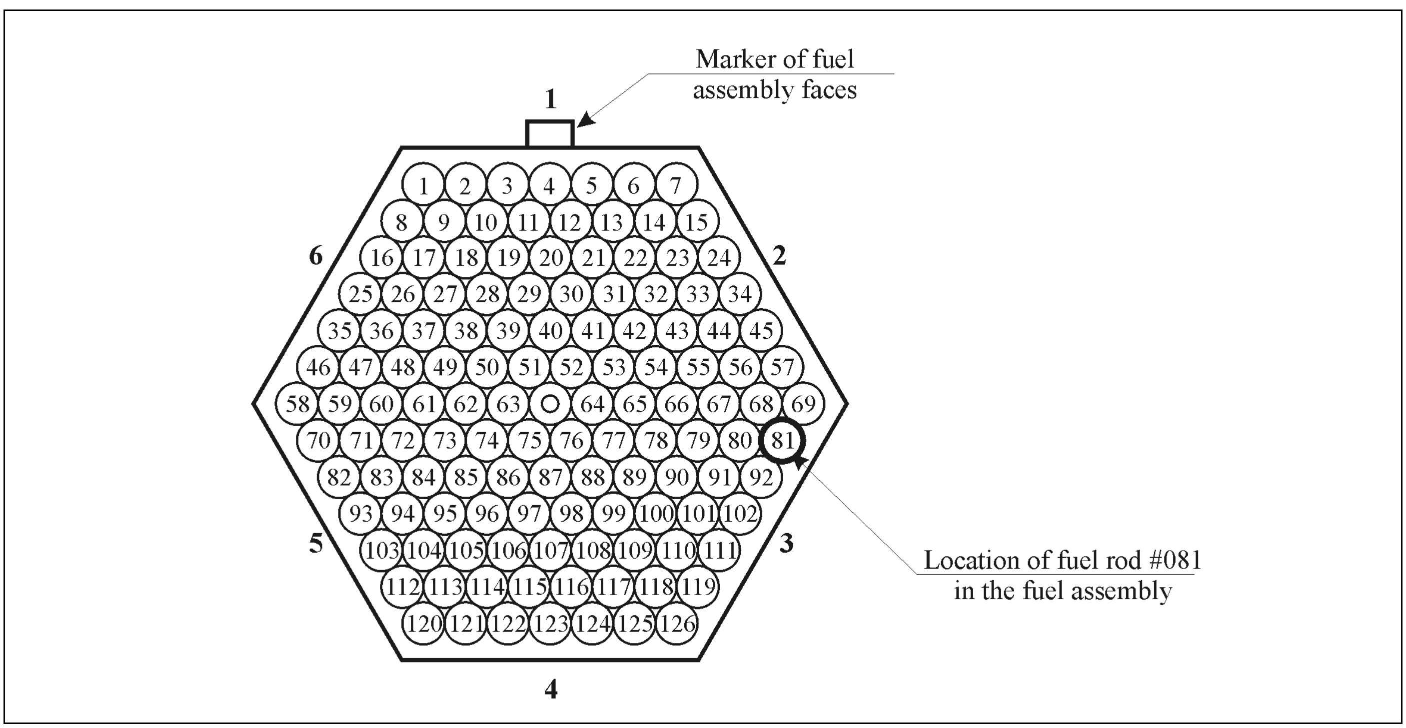


Fig. B.2. Arrangement of fuel rods in the fuel assembly #222

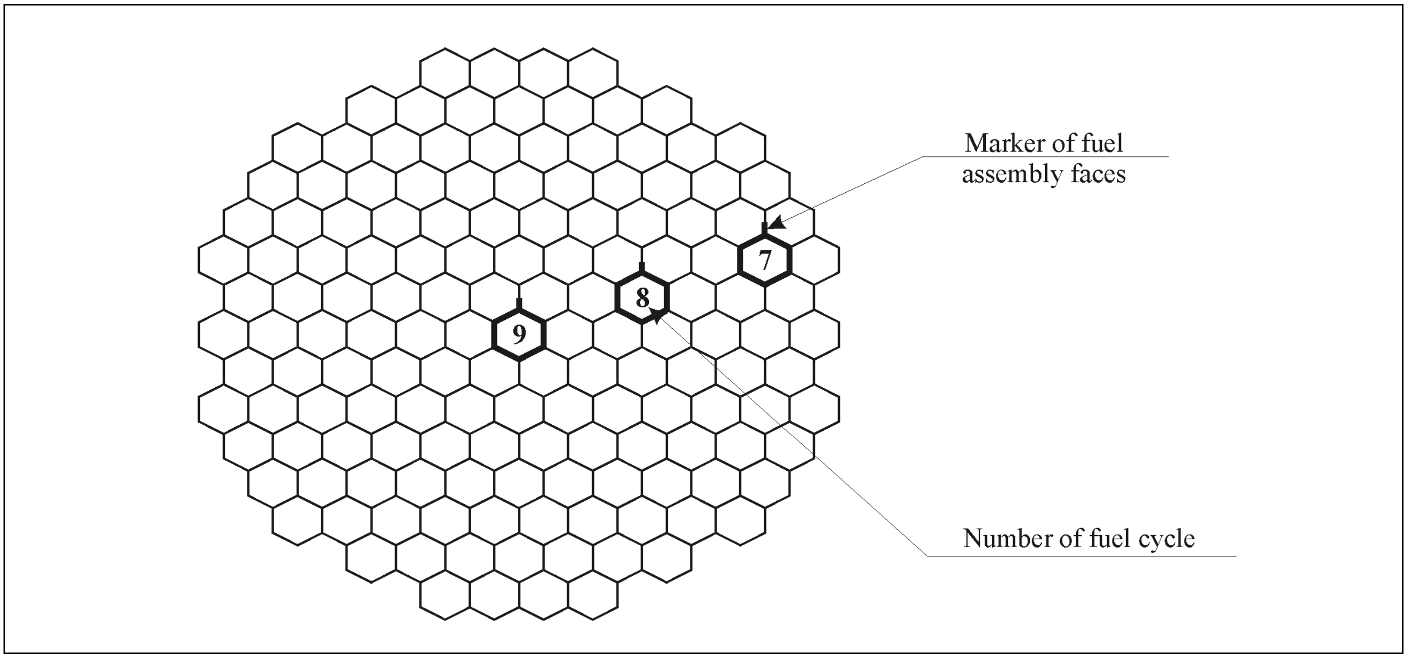


Fig. B.3. Arrangement of fuel assembly #ED4108 (108) in the reactor core

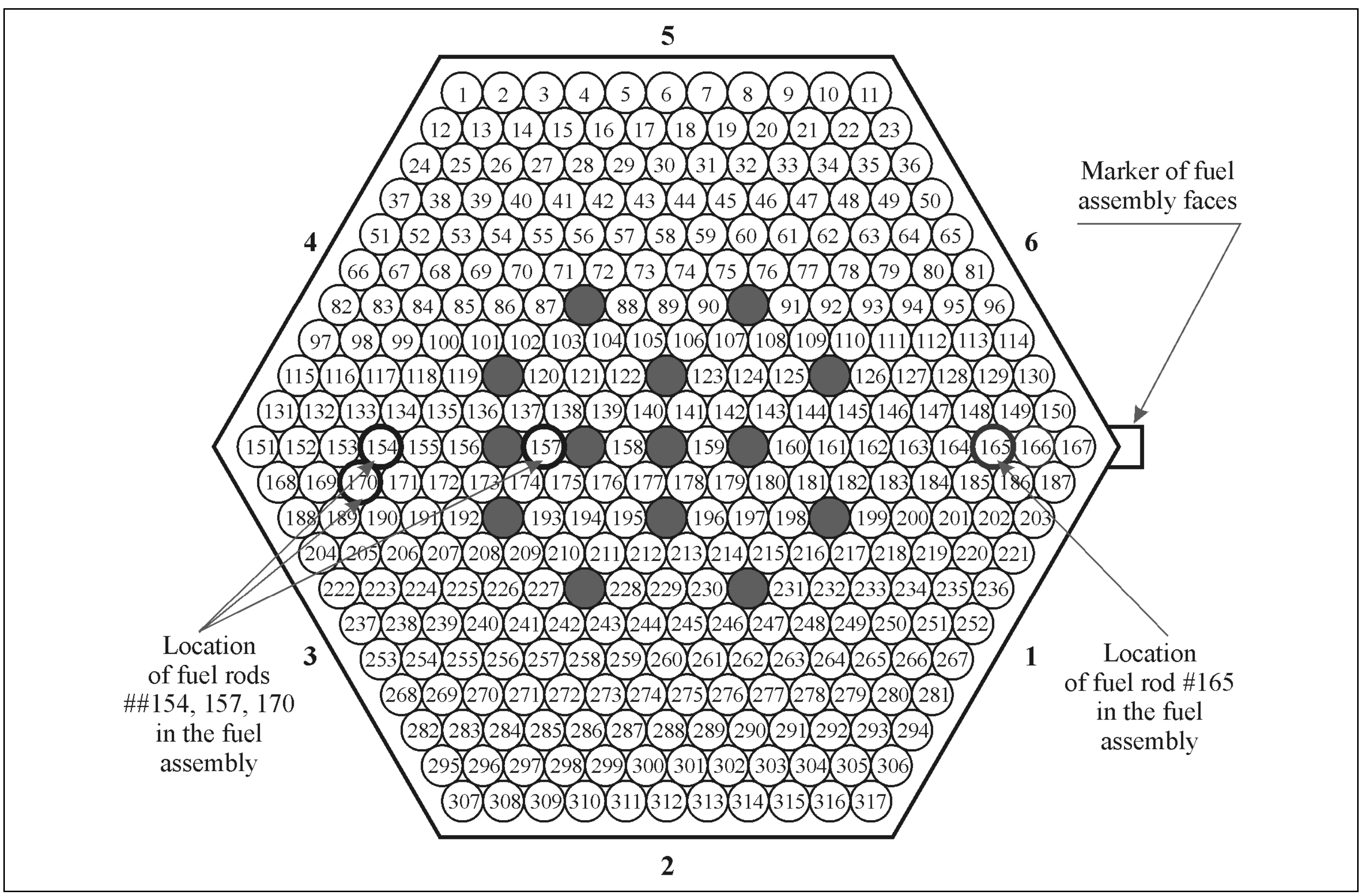


Fig. B.4. Arrangement of fuel rods in the fuel assembly #ED4108 (108)

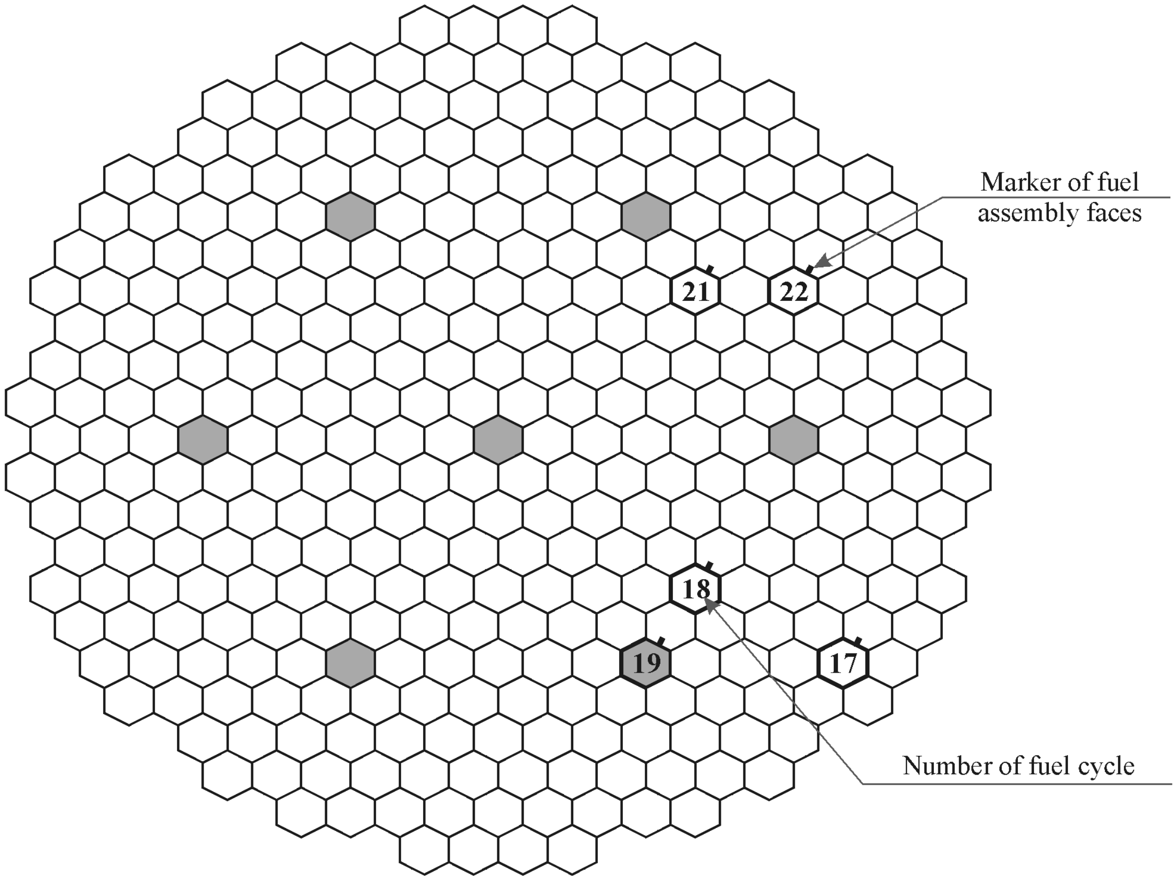


Fig. B.5. Arrangement of fuel assembly #23635228 (228) in the reactor core

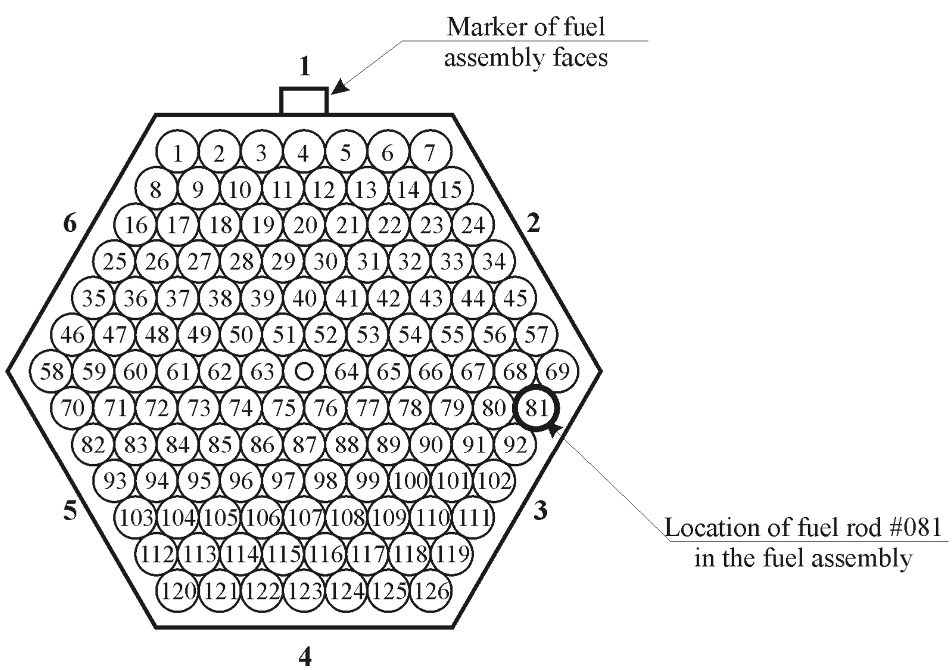


Fig. B.6. Arrangement of fuel rods in the fuel assembly #228

Table B.4. Characteristics of commercial fuel rods used for the refabrication after the base irradiation (in accordance with PIE results)

Characteristic	Unit	Value					
Fuel rod type	–	VVER-440	VVER-1000	VVER-1000	VVER-1000	VVER-1000	VVER-440
Number of fuel assembly	–	222	108	108	108	108	228
Number of fuel rod (see Fig. B.2, Fig. B.4, Fig. B.6)	–	081	154	157	165	170	081
Commercial number of fuel rod	–	18801/75	E023269	E023261	E023267	E023404	–
Fuel rod							
Gas pressure	MPa	1.26	2.64	2.93	2.86	2.87	1.08
He content in the gas composition	% by volume	67.72	95.65	92.58	94.69	96.61	86.05
Kr and Xe content	% by volume	28.84	4.01	6.94	4.62	3.25	13.73
FGR	% by volume	2.82	2.41	4.46	2.85	2.08	1.15
Radial fuel/cladding gap*	mm	0	0.032	0.017	0.025	–	–
Internal void volume	cm^3	10.4	35.4	33.3	32.7	33.4	10.1
Fuel							
Average burnup	MW d/kg U	52.35	43.54	44.49	44.01	44.5	55.4
Maximum burnup	MW d/kg U	61.58	49.01	50.12	49.62	47.8	61.7
Fuel outer diameter	mm	7.61	7.62	7.66	7.57	7.66	7.68
Fuel inner diameter	mm	1.70	2.50	2.50	2.46	2.50	1.65
Density*	g/cm^3	10.1–10.3	10.3–10.5	10.3–10.5	10.3–10.5	10.3–10.5	–
Grain size*	μm	3	3–8	3–8	3–8	3–8	–
Rim layer thickness	mm	0.15–0.20	0.05–0.07	0.05–0.07	0.05–0.07	0.05–0.07	–
ZrO_2 outer thickness*	μm	3–5	3–5	3–5	3–5	3–5	3–5
ZrO_2 inner thickness*	μm	10	0	0	0	0	8–10
Cladding							
Average diameter along upper plenum	mm	9.137	9.14	9.14	9.14	9.154	9.101
Average diameter along fuel stack	mm	9.07	9.08	9.08	9.07	9.083	9.045
Average thickness	mm	0.73	0.70	0.69	0.72	0.69	–
H_2 content	% by weight	$6–8·10^{-3}$	$5·10^{-3}$	$5·10^{-3}$	$5·10^{-3}$	$5·10^{-3}$	–
ZrO_2 outer thickness	μm	3–5	3–5	3–5	3–5	3–5	3–5
ZrO_2 inner thickness	μm	0–10	0	0	0	0	0–10

* This parameter characterizes that part of the fuel element, which was used for the refabrication

Table B.5. The calculated linear heat rating of VVER-1000 fuel elements during the base irradiation at elevations used for the manufacture of refabricated fuel rods

Number of fuel element*	Elevation (mm)	Number of refabricated fuel rod	Linear heat rating (kW/m)					
			7th cycle		8th cycle		9th cycle	
			B**	E***	B	E	B	E
154	2180	RT6	26.0	23.7	23.3	17.7	18.0	15.0
157	2410	RT5	24.0	22.0	25.3	19.0	18.7	15.7
165	1120	RT1	27.0	26.0	23.3	19.0	18.3	15.0
165	1350	RT2	27.0	25.3	24.0	18.7	18.3	14.3
165	2410	RT3	24.7	24.0	23.7	18.7	18.7	15.0
170	2180	RT10	27.0	24.2	23.3	17.7	18.3	14.7
170	2410	RT11	25.7	24.3	23.7	17.7	18.0	14.7
170	2650	RT12	25.0	24.0	23.7	18.0	18.0	15.3

* Numbers are presented in accordance with Fig. B.4
** The Beginning (B) of cycle
*** The End (E) of cycle

Table B.6. The calculated linear heat rating of VVER-440 (FA #222) fuel elements during the base irradiation at elevations used for the manufacture of refabricated fuel rods

Number of fuel element*	Elevation (mm)	Number of refabricated fuel rod	Linear heat rating (kW/m)									
			5th cycle		6th cycle		7th cycle		8th cycle		9th cycle	
			B**	E***	B	E	B	E	B	E	B	E
81	860	RT4	15.0	13.3	20.0	16.0	17.7	15.0	15.3	13.3	12.0	10.7
81	970	RT8	15.0	13.3	20.0	16.3	18.0	15.0	15.7	13.3	12.0	10.7
81	1210	RT9	15.7	13.3	19.3	16.7	17.0	15.0	15.0	13.7	11.3	11.0

* Numbers are presented in accordance with Fig. B.4
** The Beginning (B) of cycle
*** The End (E) of cycle

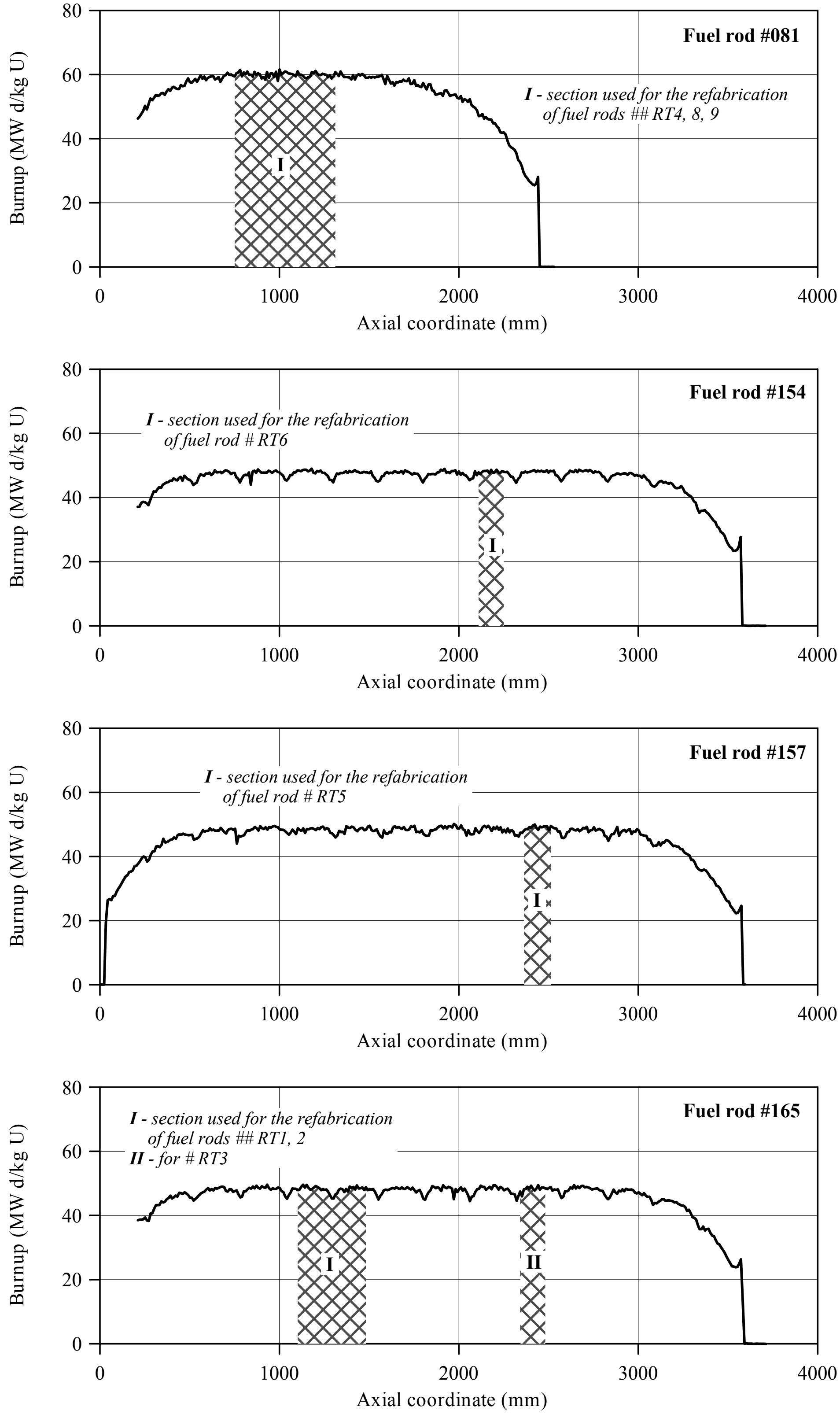


Fig. B.7. Axial distribution of fuel burnup in fuel rods ## 081, 154, 157, 165 of fuel assemblies ##222, 108

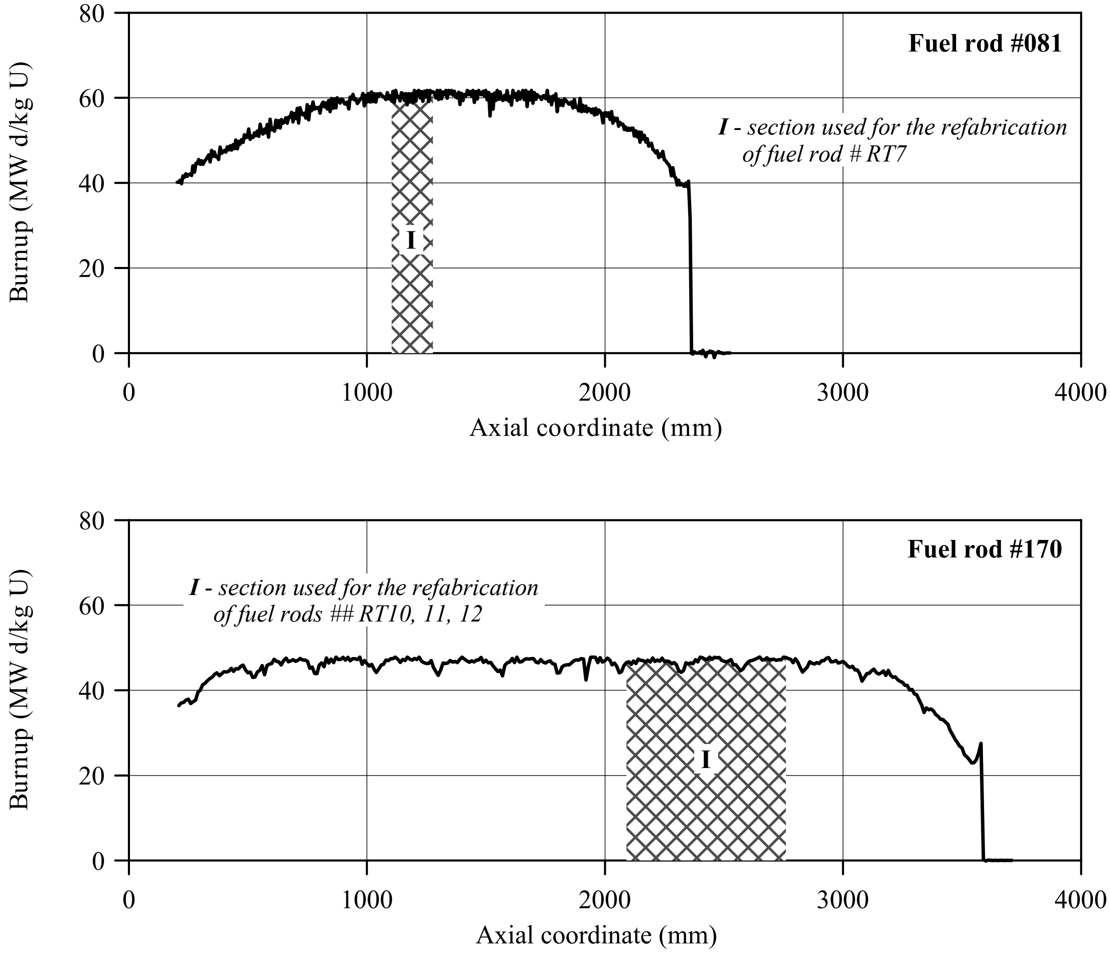


Fig. B.8. Axial distribution of fuel burnup in fuel rods ## 081, 170 of fuel assemblies ##228, 108

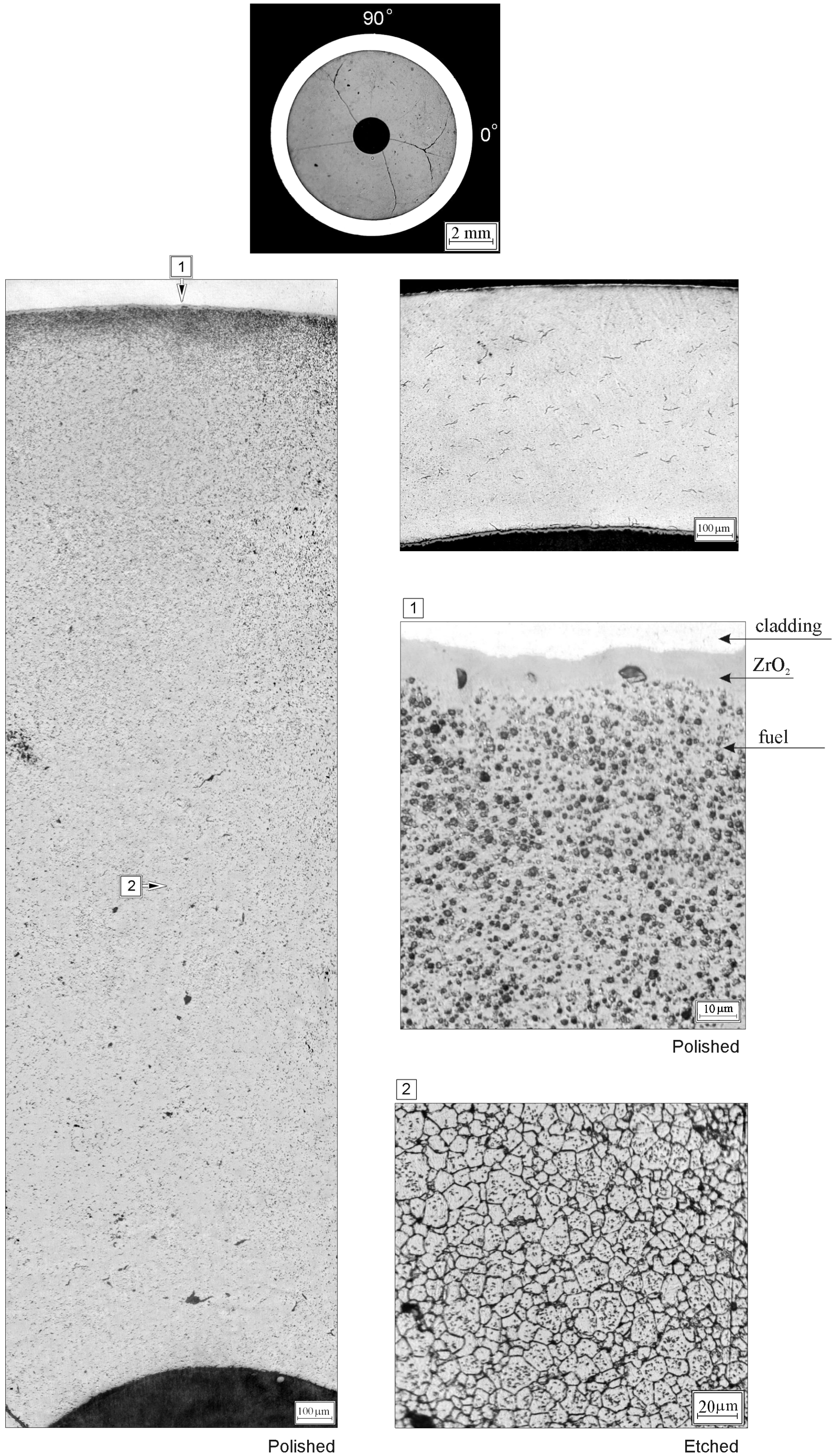


Fig. B.9. Macro- and microstructures of fuel and cladding in commercial fuel rod #081 (VVER-440, fuel assembly #222) at 1110 mm elevation after the base irradiation

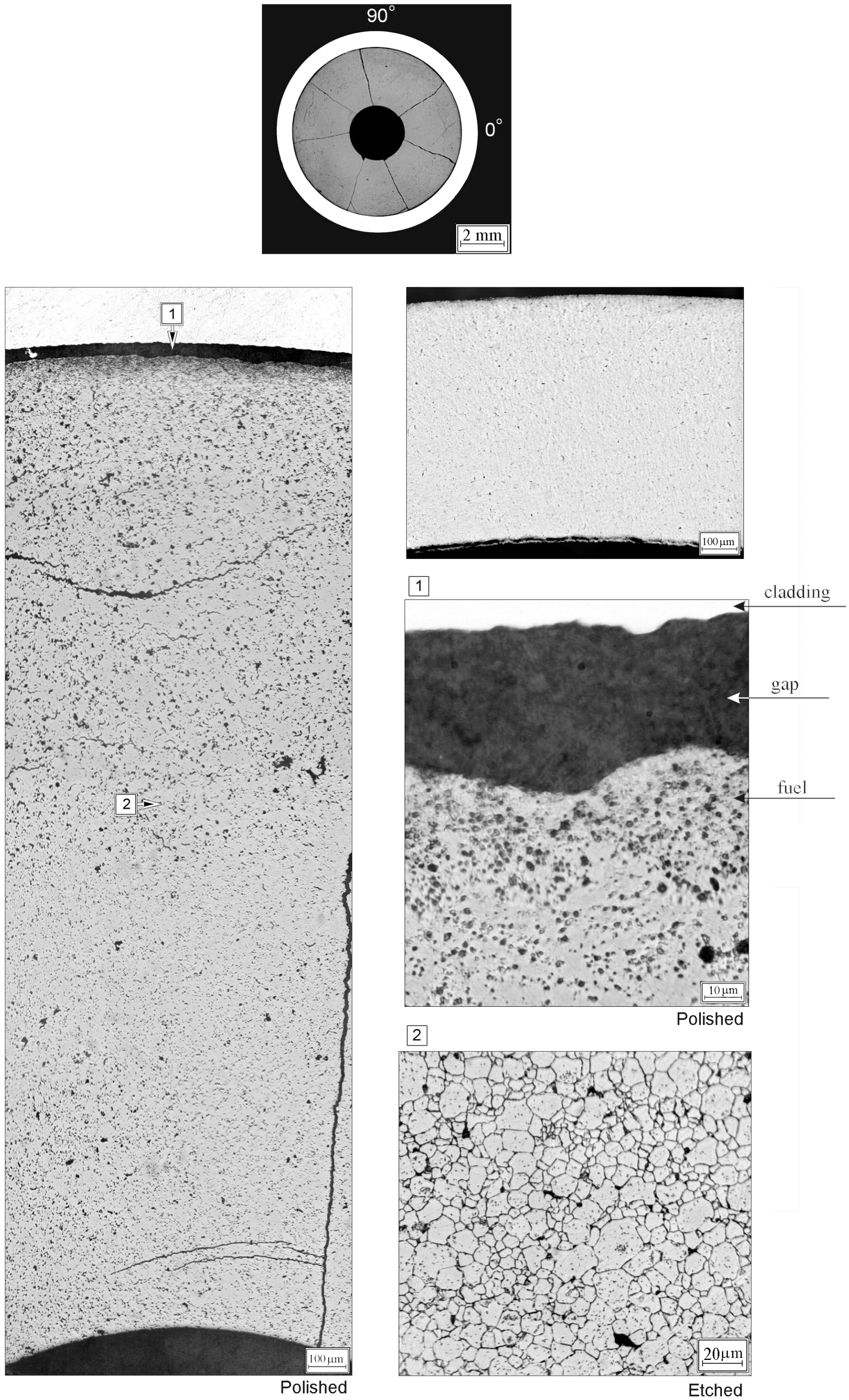


Fig. B.10. Macro- and microstructures of fuel and cladding in commercial fuel rod #154 (VVER-1000, fuel assembly #108) at 2080 mm elevation after the base irradiation

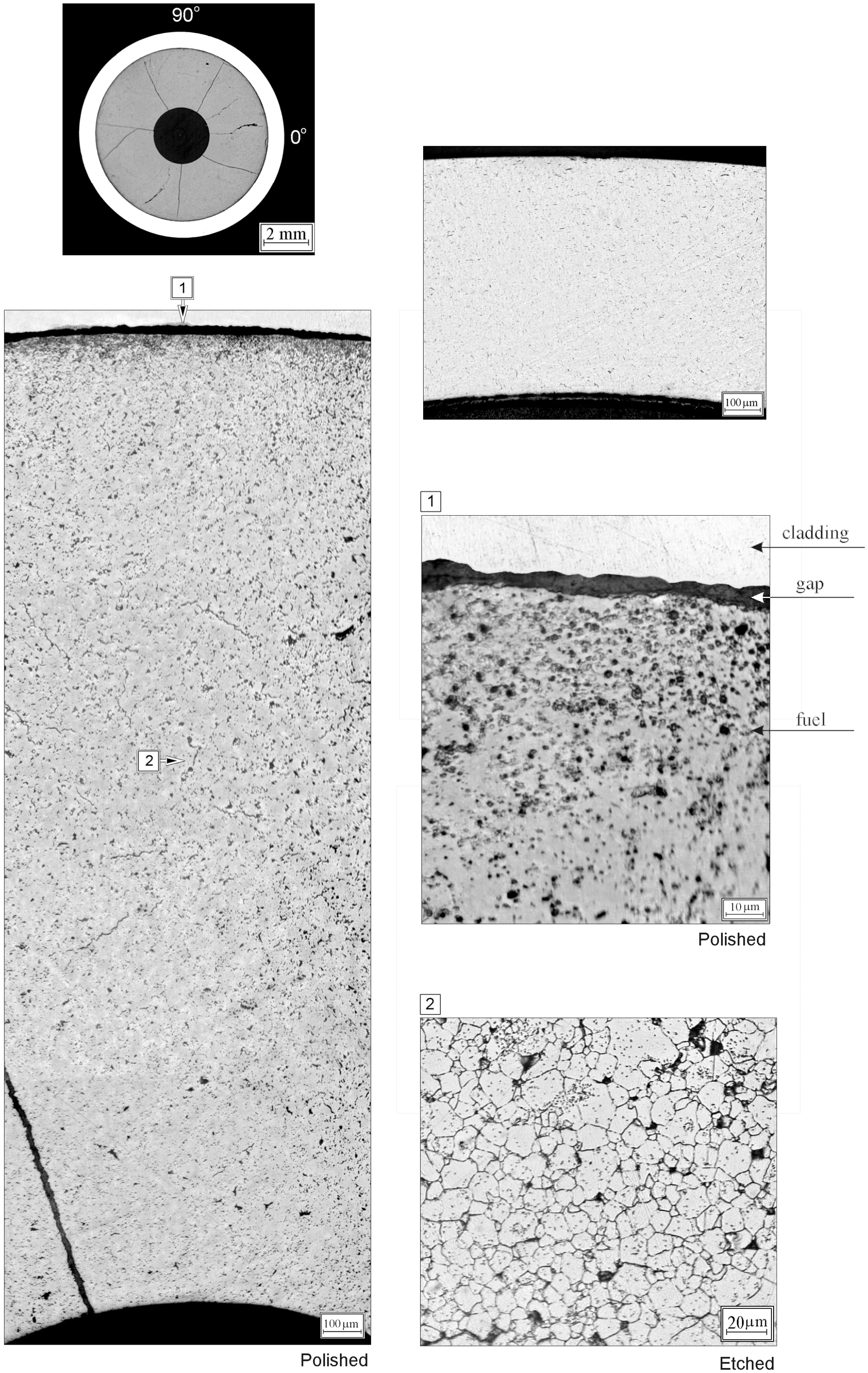


Fig. B.11. Macro- and microstructures of fuel and cladding in commercial fuel rod #157 (VVER-1000, fuel assembly #108) at 2340 mm elevation after the base irradiation

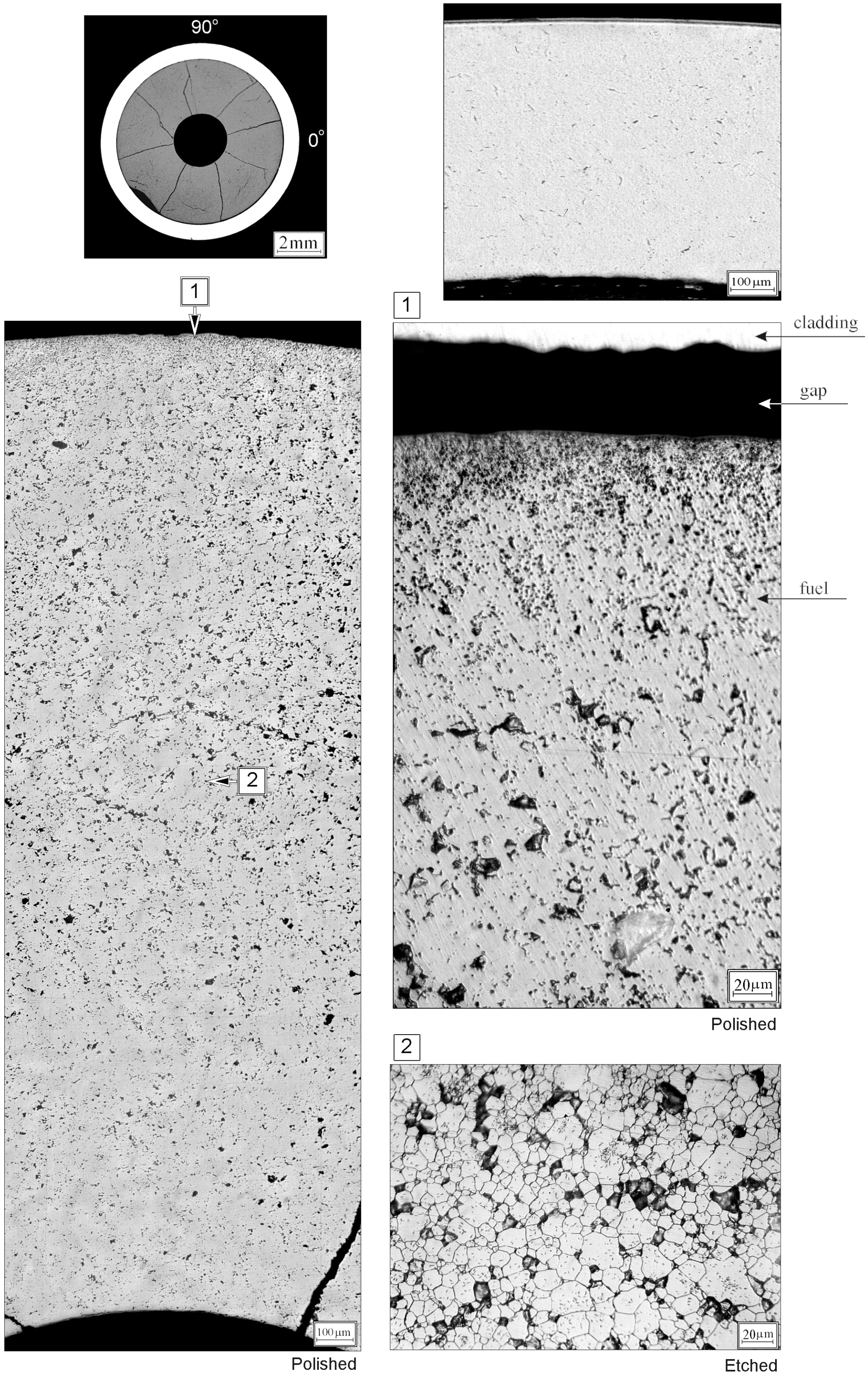


Fig. B.12. Macro- and microstructures of fuel and cladding in commercial fuel rod #165 (VVER-1000, fuel assembly #108) at 1495 mm elevation after the base irradiation

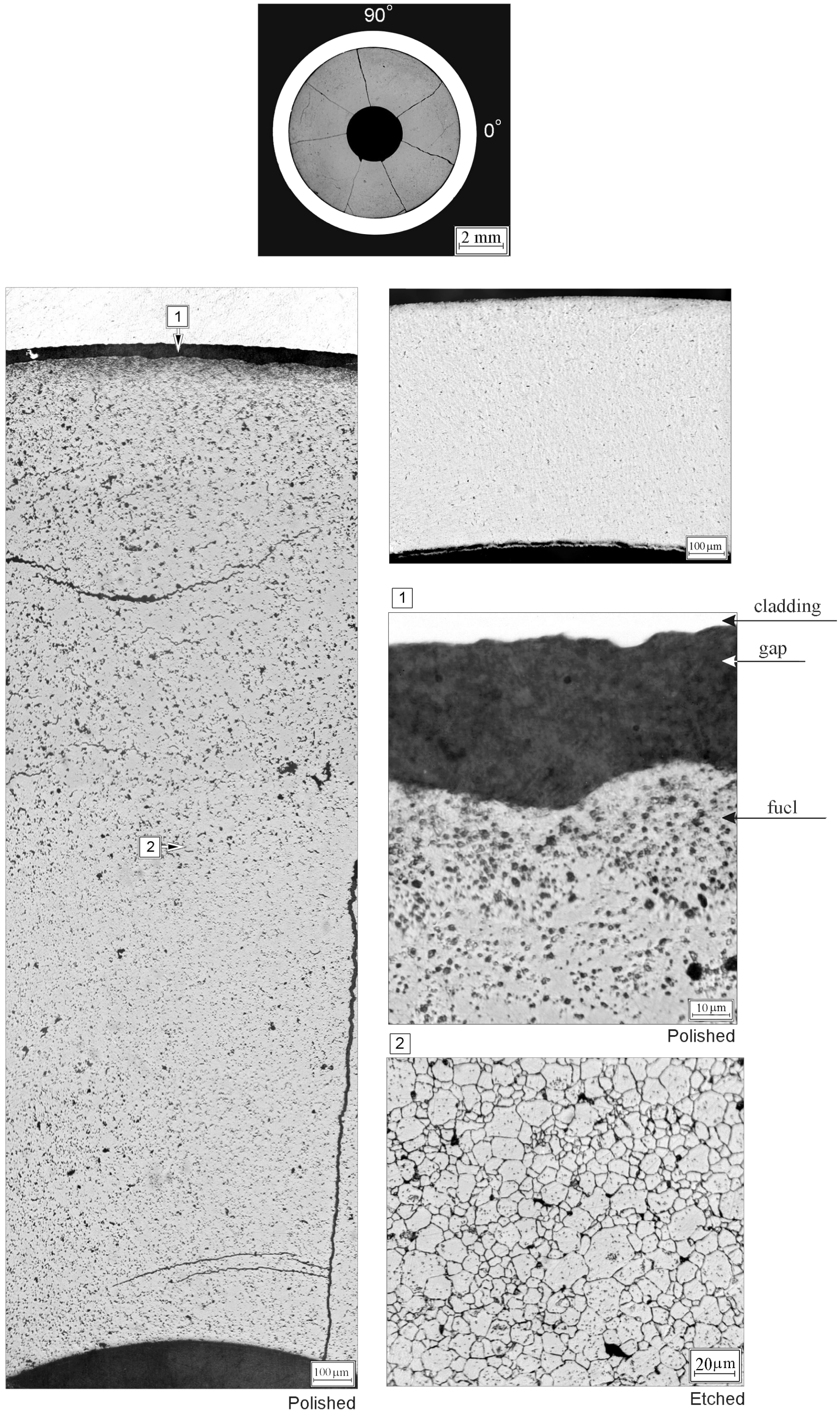


Fig. B.13. Macro- and microstructures of fuel and cladding in commercial fuel rod #170 (VVER-1000, fuel assembly #108) at 2270 mm elevation after the base irradiation

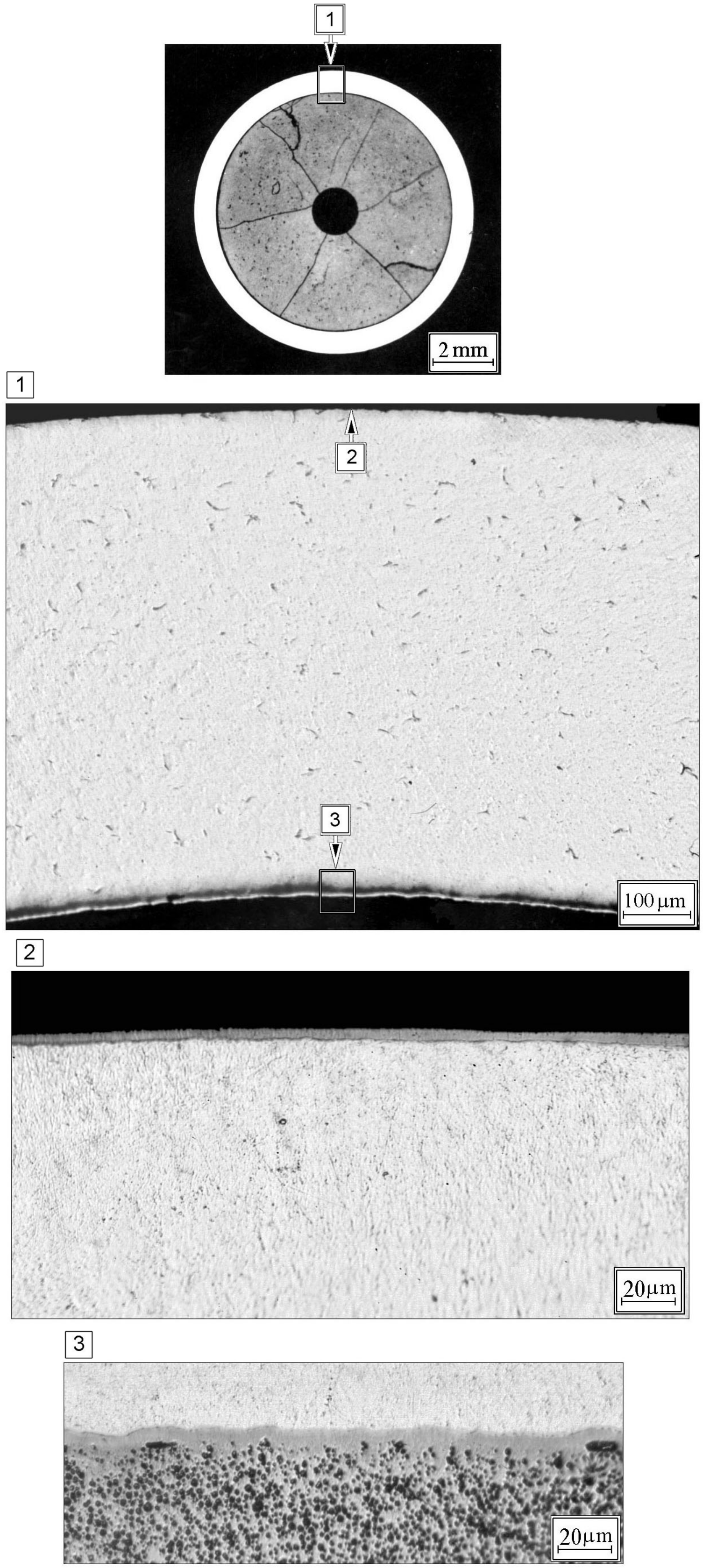
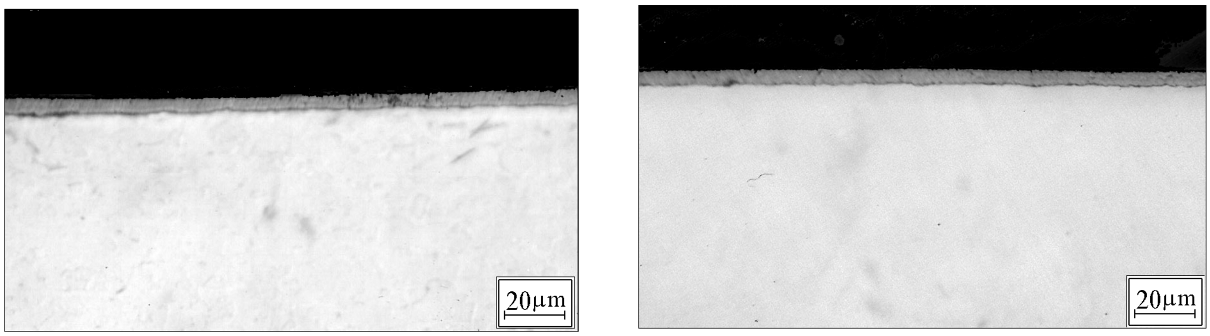


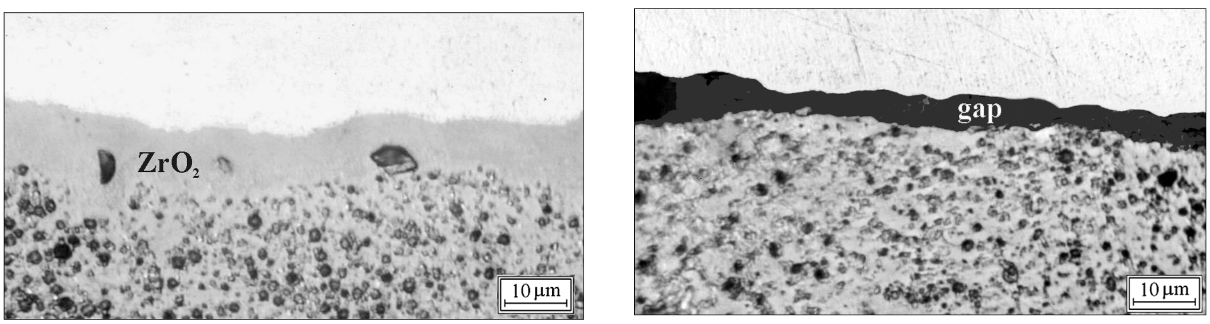
Fig. B.14. Macro- and microstructures of fuel and cladding in commercial fuel rod #081 (VVER-440, fuel assembly #228) at 1300 mm elevation after the base irradiation

Fuel rod #081 at elevation 1110 mm
(fuel assembly #222)
60 MW day/kg U

Fuel rod #157 at elevation 2340 mm
(fuel assembly #108)
50 MW day/kg U



Cladding outer surface



Cladding inner surface

Fig. B.15. Comparative data characterizing the cladding oxidation and fuel/cladding gap at burnup 50 and 60 MW d/kg U

APPENDIX C

CHARACTERISTICS OF REFABRICATED FUEL RODS BEFORE THE BIGR TESTS

Table C.1. Characteristics of fuel rods before BIGR tests: Reference data*

Characteristic	Unit	Value		
Commercial fuel rod type	–	VVER-440	VVER-1000	VVER-440
Number of fuel assembly	–	222	4108	228
Number of commercial fuel rod	–	081	154, 157, 165, 170	081
Number of refabricated fuel rod	–	RT 4, 8, 9	RT 1, 2, 3, 5, 6, 10, 11, 12	RT 7
1. Fuel				
1.1. Outer diameter	mm	7.61	7.57–7.66	7.68
1.2. Inner diameter	mm	1.7	2.46–2.5	1.65
1.3. Density	g/cm^3	10.1–10.3	10.3–10.5	–
1.4. Grain size	μm	3	3–8	–
2. Cladding				
2.1. Outer diameter	mm	9.07–9.09	9.06–9.08	9.06
2.2. Thickness	mm	0.73	0.69–0.72	0.69
2.3. ZrO_2 outer thickness	μm	3–5	3–5	3–5
2.4. ZrO_2 inner thickness	μm	10	0	8–10
2.5. Hydrogen content	% by weight	$6–8\cdot10^{-3}$	$5\cdot10^{-3}$	–
3. Refabricated fuel rod				
3.1. Design	–	RT4 see Fig. C.1 RT8, 9 see Fig. C.2	see Fig. C.1	see Fig. C.1
3.2. Gas composition	–	He	He	He

Table C.2. Individual parameters of refabricated fuel rods ## RT1–6 before BIGR tests**

Parameter	Number of fuel rod					
	RT1	RT2	RT3	RT4	RT5	RT6
Number of mother fuel rods	165	165	165	081	157	154
Coordinates of mother fuel rod section used for refabrication*** (mm)	1093 1246	1331 1482	2340 2489	745 900	2360 2513	2103 2254
Pellet stack coordinate*** (mm)	24 177	25.4 176.4	23.6 172.6	22 177	24 177	23 174
Coordinates of undamaged section of pellet stack**** (mm)	24 177	25.4 176.4	65.5 110.5	22 177	24 177	23 165
Undamaged section length (mm)	153	151	45	155	153	142
Average burnup (MW d/kg U)	48.3	48.0	47.5	60.1	48.6	47.8
Total fuel mass (g)	63.5	62.1	60.4	69.5	63.1	61.9
Mass of undamaged fuel section (g)	63.5	62.1	18.36	69.5	63.1	58.4
L_1***** (mm)	4.6	6.0	4.2	2.6	4.6	3.6
L_2***** (mm)	153	151	149	155	153	151
L_3***** (mm)	4.5	3.1	3.4	2.5	2.5	2.5
L_4***** (mm)	302	300	296.5	300	300	297
Total gas volume (cm^3)	6.13	6.12	6.08	5.54	6.07	6.03
Cladding outer diameter (mm)	9.06	9.06	9.06	9.08	9.06	9.07
Fuel-cladding radial gap (mm)	0.025	0.025	0.025	0.000	0.017	0.032
Central hole diameter (mm)	2.46	2.46	2.46	1.65	2.50	2.50
Internal gas pressure (MPa)	2.1	2.1	2.1	2.1	2.1	2.1

* Characteristics were developed in accordance with data of Table B.4.
** Parameters were determined using pre-test examination results
*** From lower cap of fuel rod
**** Taking into account the risk of fuel damage at the refabrication procedure, special measurements were performed to estimate the coordinates of that part of fuel stack, which was identified as "undamaged" after the refabrication. The coordinates of undamaged part was determined from lower cap of fuel rod
***** See Fig. C.1

Table C.3. Individual parameters of refabricated fuel rods ## RT7–12 before BIGR tests *

Parameter	Number of fuel rod					
	RT7	RT8	RT9	RT10	RT11	RT12
Number of mother fuel rods	081	081	081	170	170	170
Coordinates of mother fuel rod section used for refabrication ** (mm)	1100 1278	931 1109	1133 1311	2090 2268	2343 2522	2590 2769
Pellet stack coordinate ** (mm)	23 176.1	7 157	8 157	21.4 173.4	23 175	21.3 173.9
Coordinates of undamaged section of pellet stack *** (mm)	23 176.1	7 157	8 157	21.4 173.4	23 175	21.3 173.9
Fuel stack length (mm)	153.1	150	149	152	152	152.6
Average burnup (MW d/kg U)	60.5	60.0	59.8	46.9	47.2	47.3
Total fuel mass (g)	66.8	66.2	66.2	62.6	62.9	63.0
L_1**** (mm)	3.6	0.0	0.0	2.0	3.6	1.9
L_2**** (mm)	153.1	150.0	149.0	152.0	152.0	152.6
L_3**** (mm)	2.4	9.1	10.1	5.1	3.5	5.6
L_4**** (mm)	299	299	299	299	299	300
Total gas volume (cm^3)	5.75	5.93	5.88	6.10	6.23	6.11
Cladding outer diameter (mm)	9.062	9.09	9.07	9.072	9.08	9.066
Fuel-cladding radial gap (mm)	0.003	0.003	0.001	0.023	0.018	0.012
Central hole diameter (mm)	1.65	1.65	1.65	2.50	2.50	2.50
Internal gas pressure (MPa)	2.0	2.0	0.1	2.0	2.0	0.1

* Parameters were determined using pre-test examination results
** From lower cap of fuel rod
*** Taking into account the risk of fuel damage at the refabrication procedure, special measurements were performed to estimate the coordinates of that part of fuel stack, which was identified as “undamaged” after the refabrication. The coordinates of undamaged part was determined from lower cap of fuel rod
**** See Figs. C.1, C.2

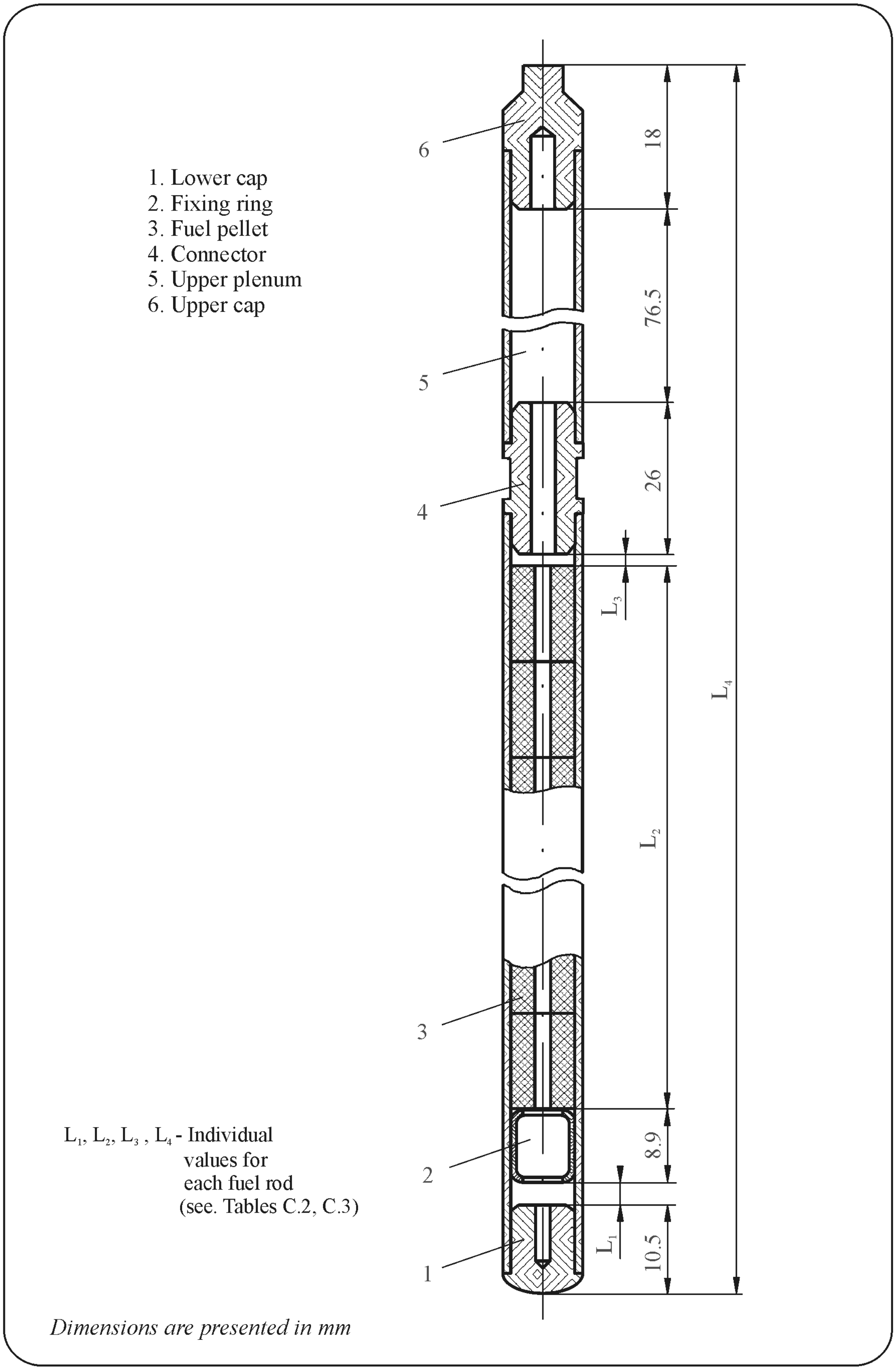


Fig. C.1. Design scheme of refabricated fuel rods ## RT 1–7, 10, 12

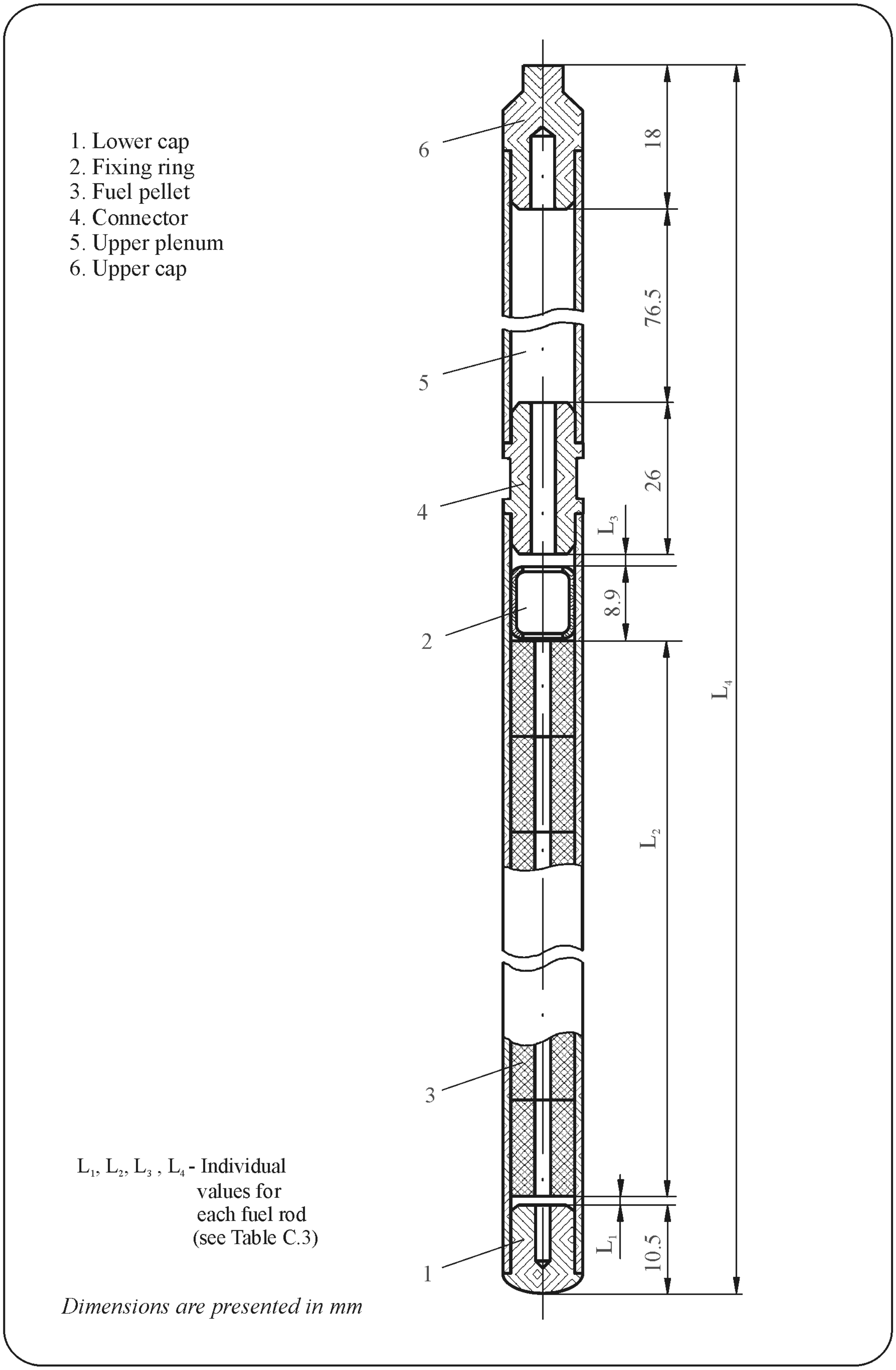


Fig. C.2. Design scheme of refabricated fuel rods ## RT8, 9