Acceptance Test of WCTC with LEU fuel

at the IVG.1M Research Reactor Site in Kazakhstan

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RERTR 2022
International Meeting on
Reduced Enrichment for
Research and Test Reactors
October 3-5, 2022
Vienna, Austria

National Nuclear Security Administration

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Overview

- **Project background**
  - Historical overview
  - Introduction of the IVG.1M reactor and the water-cooled technological channels (WTCC)
  - Water-cooled technological channels (WTCC) and fuel rods
  - Outdoor and indoor installations
- **Acceptance Test Program (ATC)**
  - Sampling
  - Test programs
  - Training materials
- **Site Acceptance Test (SAT)**
  - Non-destructive tests
  - Destructive tests
  - WCTC-LEU assemblies' verification
- **Conclusion**

Historical Overview

- IVG.1M reactor belongs to the National Nuclear Center of Kazakhstan and is located at the Baikal-1 site near Kurchatov City
- Feasibility study on possible conversion of the IVG.1M reactor to LEU fuel was completed in 2013
- Two LEU lead test assemblies for IVG.1M reactor were delivered to Kazakhstan in 2014; the in-reactor test of IVG LEU fuel assemblies started on October 17, 2017
- LEU fuel irradiation testing was completed in October 2019
- Post Irradiation Examination was completed in May 2020
- LEU fuel was delivered to NNC in February 2021
- Non-destructive and destructive tests of new LEU fuel were completed in September 2021

General view of the LEU fuel assembly

IVG.1M reactor

Control room of IVG.1M reactor

Delivery of LEU fuel assemblies to NNC

LEU fuel arrives to NNC

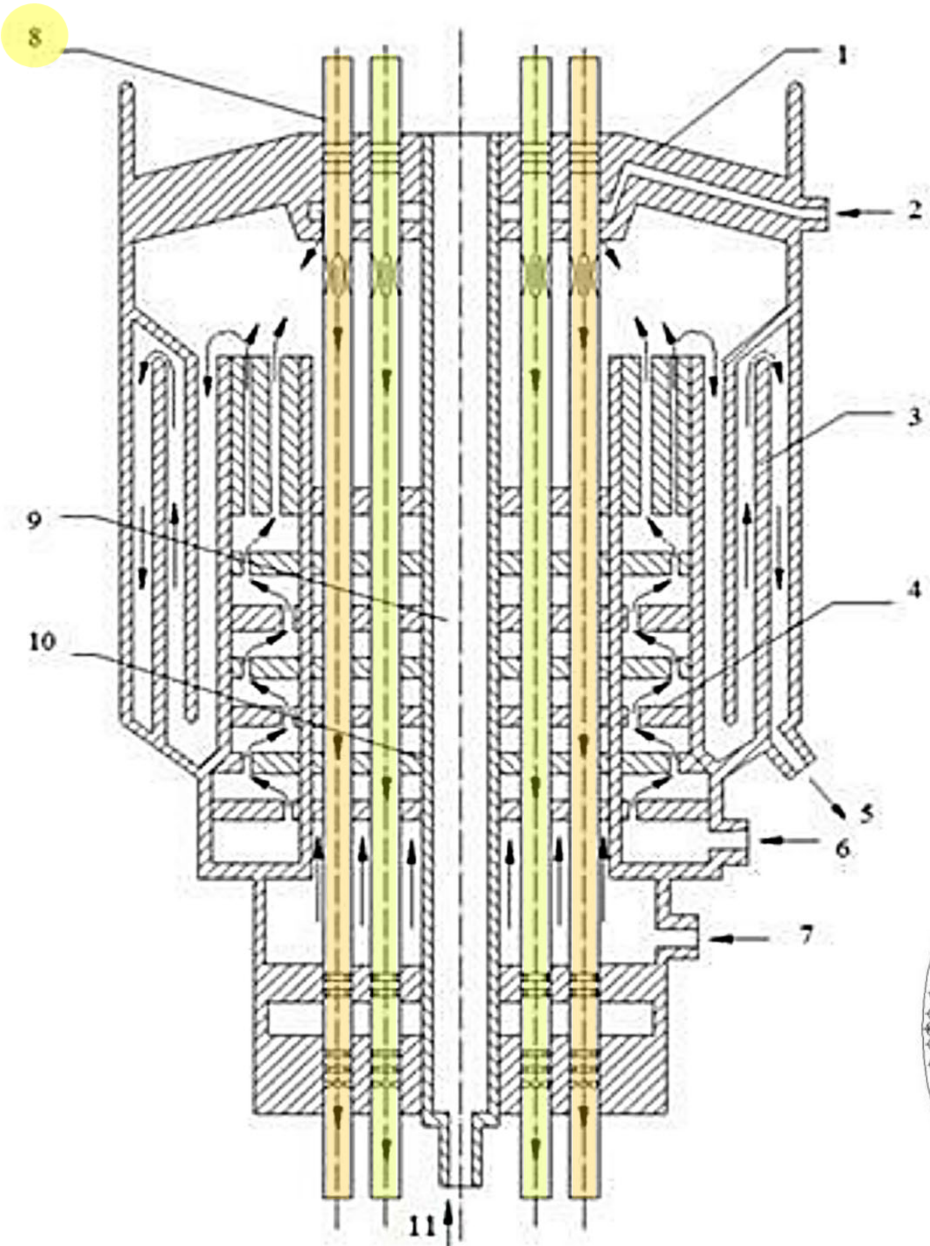
Loading of LEU fuel into IVG.1M storage

NNSA team observes LEU fuel (November 2021)

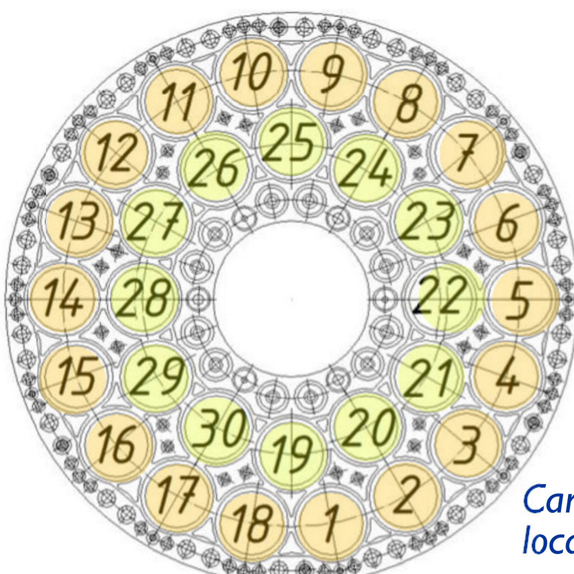
LEU fuel assemblies after inspection

IVG.1M core scheme

- IVG.1M has vessel and channel type features
- The channel characteristics are provided by the special WCTCs that contain nuclear fuel
- Core components are: 1 – lid; 2 – supply of water into lid; 3 – heat screens; 4 – reflector; 5 – water draining from the case; 6 – supply of water into reflector; 7 – supply of water into central assembly; 8 – WCTC; 9 – loop channel; 10 – central assembly; 11 – supply of water into loop channel
- WCTC's dimensions: length 4990 mm; ∅ 76 mm
- Number of WCTCs: 30



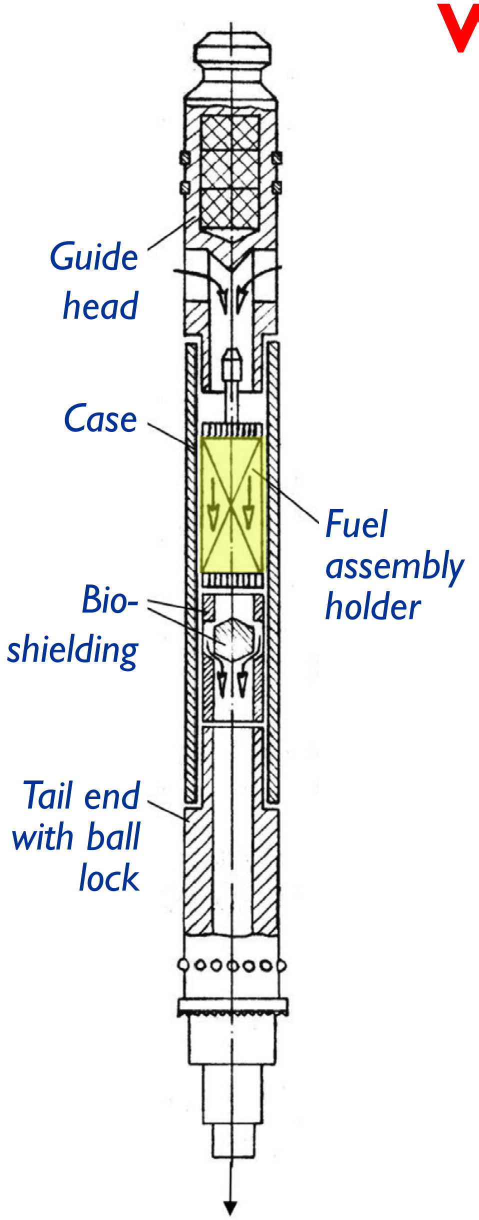
IVG.1M reactor's core scheme with the indication of coolant flow direction



Cartogram of the WCTC location in the IVG.1M reactor's core

- WCTCs are located in two rings
- Length of fuel rods in WCTCs:
  - ✓ in outer ring 800 mm
  - ✓ in inner ring: 600 mm

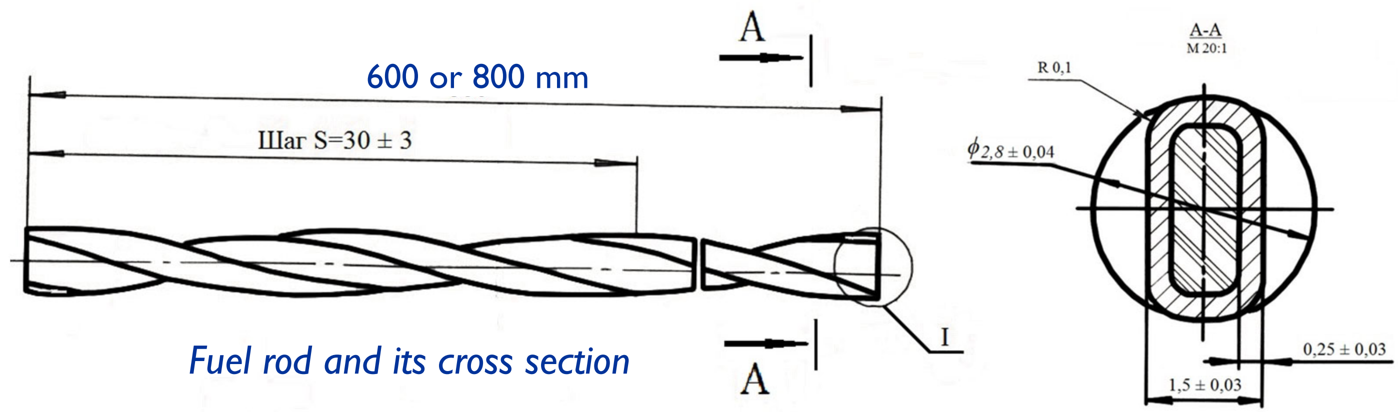
Water-Cooled Technological Channel (WCTC) and its fuel pin



Functional and nodal scheme of the WCTC

WCTC capsule

- The fuel assembly sleeve is located in the middle section of the capsule. It contains a package of a set of spiral fuel rods.



Fuel rod and its cross section

Fuel rod

- The spiral fuel rod element is made in the form of a two-blade profile and consists of a metallurgically bonded cladding and fuel meat.
- Cladding material: zirconium alloy E110 on the ends with nickel coating.
- Fuel meat: a composition made of zirconium alloy E110 with uranium filaments evenly distributed.
- U-235 enrichment is 19.75% in case of LEU fuel.
- Length of the rod in case of WCTCs:
  - ✓№ 1÷18 is 800 mm,
  - ✓№ 19÷30 is 600 mm.

TD and ATP for WCTC-LEU production

- **Based on the in-pile test results the National Nuclear Center of Kazakhstan (NNC) agreed that:**
  - The fabrication will be made according to the **original *Technical Design (TD)***
  - The WCTC-LEU's quality and its compliance verification with the TD will be checked based on an *Acceptance Test Program (ATP)* that was previously developed and adopted.

- **Acceptance Test Program (ATP):** It defines the test methods and sampling
  - **Test methods**: it consists of three groups:
    1) Non-destructive tests (NDTs);
    2) Destructive tests (NDs)
    3) WCTC-LEU assemblies' verification (V&V of WCTC).
  - **Sampling**

Sampling	NDT	DT	V&V of WCTC
52 pcs replacement rods (they were part of the delivery)	YES	X	X
Max. 5% (20 pcs) of randomly selected fuel rods from two sets of FAs.	YES	X	X
52 pcs, so called **witness rods** (2 fuel rods randomly taken out from 26 sets of FAs) for non-destructive and destructive tests	YES	YES	X
30 pcs WCTC-LEU channels	X	X	YES

Acceptance Test Program (1/3)

1) <u>Non-destructive test methods</u>

❑ **<u>Subject</u>**: 52 replace rods, 52 witness rods, 20 randomly selected rods (as defined by sampling)

❑ **Controls and/or inspection**

- Visual inspection
- Measurement of α-particle flux density on the end surfaces of fuel rods
- Measurement of the thickness of the nickel coating at the ends of the fuel rods
- Control of geometric parameters
- Determination of electrical resistance

❑ **Evaluation:**

- Summarising findings by test elements
- Verify compliance with the *Technical Design*
- Initiate corrective actions and/or justifications (if needed)
- Follow-up controls/assessment to validate and verify (V&V) of the justification
- Conclusion (qualification)

Acceptance Test Program (2/3)

2) <u>Destructive test methods</u>

- **<u>Subject</u>**: the same 52 witness rods that passed the non-destructive test (as defined by sampling)
- **Controls and/or inspection**
  - Structural analysis: assessment of fuel meat (condition of uranium filaments, presence of delamination, thickness of the Ni-coating)
  - Assessment of the uniformity of the U-235 distribution
- **Evaluation:**
  - Summarizing findings by test elements
  - Verify compliance with the *Technical Design*
  - Justification (if needed) and V&V of the justification
  - Conclusion (qualification).

Acceptance Test Program (3/3)

3) <u>WCTC-LEU assemblies' verification</u>

<u>Subject</u>: the complete 30 pcs WCTC-LEU channels (as defined by sampling)

❑ **Controls and/or inspection**

- Visual inspection
- Size check
- Checking the WCTC channels for tightness and strength of connections
- Determination of the hydraulic characteristics

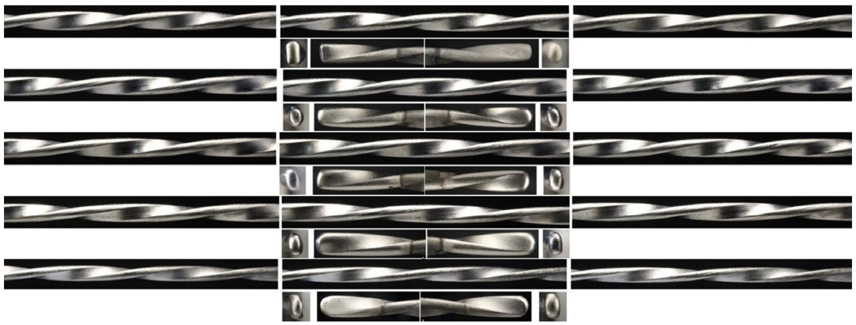
❑ **Evaluation:**

- Summarizing findings by test elements
- Verify compliance with the *Technical Design*
- Initiate corrective measures (if needed)
- Follow-up controls to validate the conformity after corrective actions
- Conclusion (qualification)

Summary of NDT

Method	Inspection technique	Requirements	Results
Visual inspection	Inspection of the rods with the naked eye	Scratch and damage free surface	Nonconformities at two fuel rod ends were revealed. **Nonconformity highlights #1** *Passed successfully*
Measurement of α-particle density on the end surfaces of fuel rods	Measurement of the rod ends with an α-particle sensitive detector. Time of measurements was 200 seconds.	Flux density of α-particles ≤ 2 counts/s/cm^2 (above the background)	The flux density at the ends of all fuel elements does not exceed the permissible limit *Passed successfully*
Measurement of the thickness of nickel coating	Measurement of the Ni-coating thickness on the rod ends	Ni-coating thickness ≥30 microns	Compliance at all rods were confirmed. *Passed successfully*
Control of geometric parameters	Parameters to be measured: 1) Diameter of the circumscribed circle (DCC), 2) Blade thickness, 3) Twist pitch and 4) Length of fuel rods	1) DCC: $2.8^{-0.04}$ mm 2) Blade thickness:$1.5^{\pm 0.03}$ 3) Twist pitch: $30^{\pm 8}$ 4) Length of fuel rods: 600^{-1}; 800^{-1}	It was found that a significant part of the fuel rods didn't correspond to the *Technical Design*. **Nonconformity highlights #2**
Determination of surface roughness parameter (Ra)	Measurement with a contact measuring device that is also suitable for measuring the curved surfaces	Ra<0.8 microns that is correspond to three wedge-quality surfaces in mechanical engineering (▽▽▽)	The measured roughness parameters don't exceed the permissible limit. *Passed successfully*
Determination of electrical resistivity (ρ)	Measurement of the electrical resistivity distribution along the entire length of the fuel rod with a step of ≈30 mm.	$\rho = 4.80^{\pm 0.25}\ \Omega \cdot cm^{-5}$	The measured values were in the permissible limit. *Passed successfully*

NCH #1 - Deficiencies detected by visual inspection



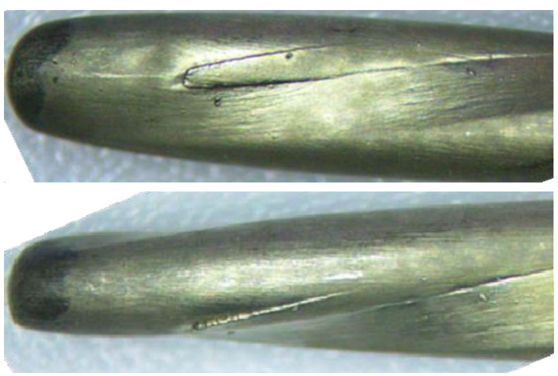
Perfect rods

- Images of exemplar fuel rods that have met the requirements

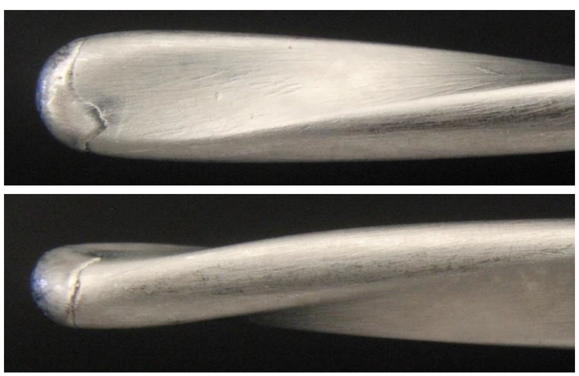
Images of the appearance of the central sections and ends of fuel rods that complied with the requirements

Two nonconformities were revealed by visual inspection:

– At one end of a fuel rod, a crack with sharp transitions was observed



– At one end of a fuel rod the presence of an influx of nickel was detected



– **Evaluation**

✓ Corrective measures initiated: since the two fuel rods belonged to the group of 52 pcs replacement fuel rods, and no other similar nonconformity was found in the group of 20 pcs randomly selected fuel rods, nor in the group of 52 witness rods, thus the two rods were transferred to the group of witness fuel rods for further destructive testing.

✓ Follow-up action: NONE. They were not considered as nonconformant in the Joint Report.

NCH #2 - DCC doesn't meet the requirements

A large number of nonconformities were caused by the tolerance value of the diameter of the circumscribed circle (DCC) of the fuel rods in terms with the *Technical Design*: $2.8^{-0.04}$ mm.

Exemplary extract from the Data sheet of the measured non-destructive test results

№	Thread pitch [mm]	Fuel rod length [mm]	Blade thickness [mm]	DCC [mm]	Thickness of Ni-coating [µm]		Density of α-particles [count/cm² min⁻¹]	
	Nominal values with tolerance limits							
	30±8	600^{-1}; 800^{-1}	$1.5^{\pm0.03}$	$2.8^{-0.04}$	>30		<2	
					T1	T2	T1	T2
1	36	599	1.49	2.76	30.0	33.9	0.51	0.82
2	33	599	1.49	2.76	64.5	34.2	0.61	0.41
3	33	600	1.48	2.77	63.3	30.3	0.51	0.52
…	…	…	…	…	…	…	…	…
50	35	799	1.49	2.77	30.63	64.89	1.02	0.71
51	37	799	1.50	2.76	30.9	30.87	0.72	0.82
52	37	799	1.49	2.76	55.23	30.75	1.33	0.72

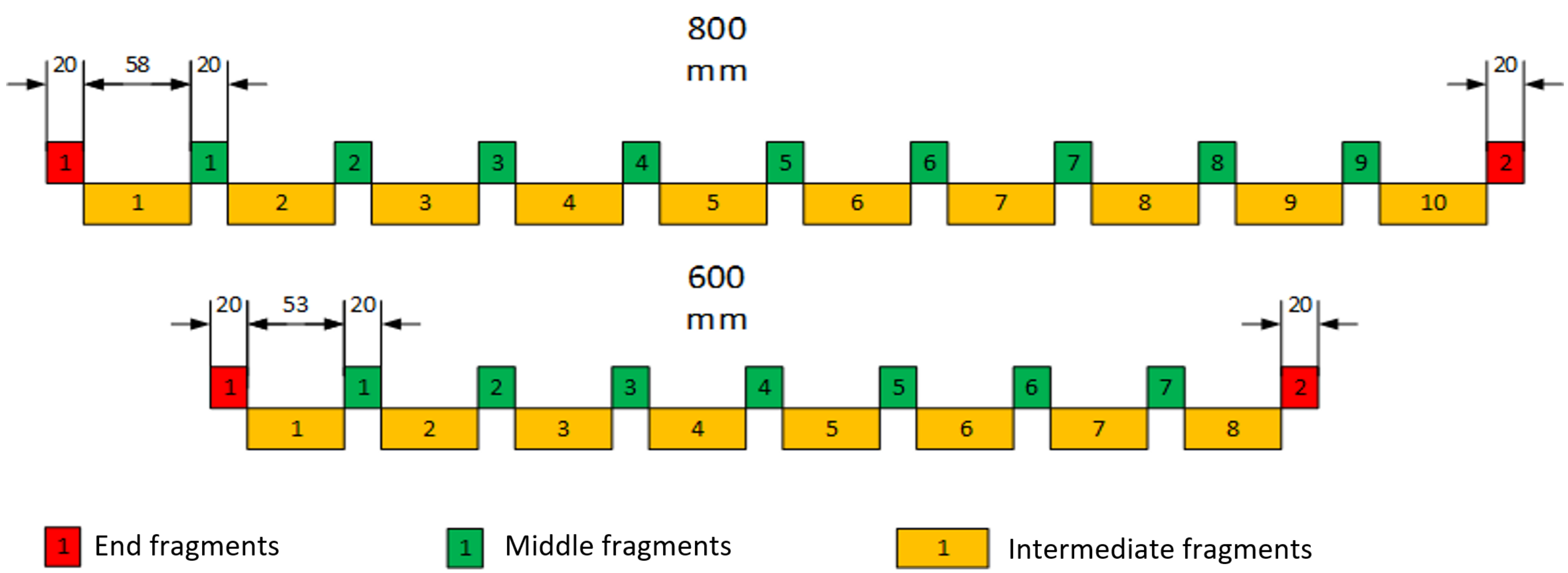
- **Justification:** upon NNC's request, the manufacturer evaluated the discrepancy. Concluded: consequence of the modified extrusion technology. Initiated the revision of the *TD* with regard to increasing the tolerance range of the DCC.
- **TD's adjustment**: change the tolerance for the DCC by the value of "-0.1 mm".

– **Verification of the justification:** to assess the impact of the initiation, **an independent expert opinion was requested by NNC**. The manufacturer's results were confirmed and declared that the initiated tolerance change doesn't influence the key critical parameters of the fuel rods. Thus, the initiated tolerance change was introduced in the *Technical Design* in the form of **Amendment № 1**.

– **Follow-up action:** based on the amended *Technical Design* and the values already measured, it was concluded that the geometric parameters of the fuel rods are satisfactory and correspond to the *Technical Design.*

Destructive tests – Sample preparation

- **Subject:** 30 witness rods (as defined by sampling)
- **Sample preparation:**
  - ✓ The fuel rods were cropped according to the scheme below



- ✓ To investigate the structural condition of the coating at the fuel rod ends ≈20 mm long fragments were separated from each fuel rod to form samples for nickel-coating investigation.
- ✓ To investigate the structural analysis of the fuel meat the test specimens were formed from segments of endless rods cropped into 8 or 10 equal pieces depending on the fuel rod length (600 or 800 mm).

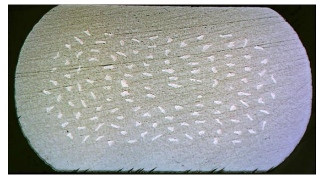
Destructive test results

Summary of the destructive testing

Method	Inspection technique	Requirements	Results
Structural analysis of – Cross-section specimens. – End-section specimens	Analysing surface morphology by optical microscope and scanning electron microscope	Presence of U-filament with an EQ∅ > 60μm, accepted threshold: 40μm	**U-filaments**: Samples from 45 fuel rods have a satisfactory fuel meat. 10 fuel rods are characterized by the presence of large filaments. **Nonconformity highlights #1**
		Delamination: <80x80μm	Delamination was found at 4 fuel rods. **Nonconformity highlights #2**
		Ni-coating thickness: 0.25±0.1 mm	Ni-coating thickness meets the requirements; the adhesion of the coating to the substrate is satisfactory. *Passed successfully*
Assessment of the uniformity of the U-235 distribution	Calculations based on the microscopic images	Uneven distribution up to 12%	The determined uneven distribution of uranium along the length of the fuel elements <4.5%. Relative error <2%. U-235 content was confirmed also *Passed successfully*

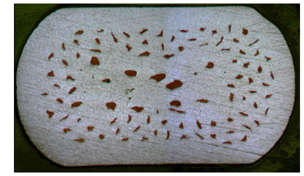
NCH #1 - Large U-filaments in the fuel meat

A typical view of the cross-section of fuel rods with a uniform and uneven distribution of uranium filaments in the fuel meat.



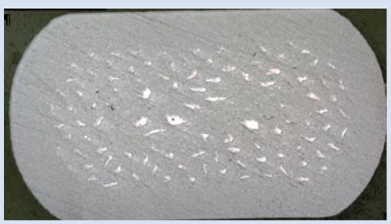
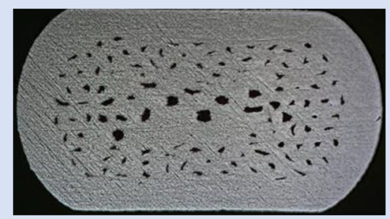
Uniform

Uneven distribution



- **Nonconformities:** ten fuel rods have over their entire length individual filaments of increased size with an equivalent diameter of more than 60 microns, and at four of them the equivalent diameter in some sections reached 100 microns along the entire length.

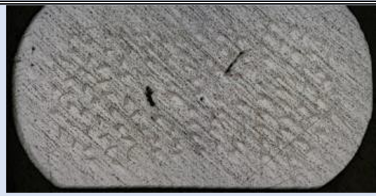
Four sections are shown as examples

Number of large filaments by size, pcs, from … to… in micron											
Fuel rod/section											
№35-2/3			№10-1/7			№3-1/6			№26-2/1		
											
60-80	80-100	100-150	60-80	80-100	100-150	60-80	80-100	100-150	60-80	80-100	100-150
2	2	2	3	4	1	8	9	2	7	5	–

- **Justification:** Manufacture, with reference to an explanatory note they had previously written, explained the phenomenon with multiple extrusion, drawing and rolling, during which the integrity of the drawn metal in the central layers inevitably occurs.
- **Verification of the justification:** independent expert opinion was requested for verification of the justification → it will be introduced at the NCH #2.

NCH #2: delamination – 1/2

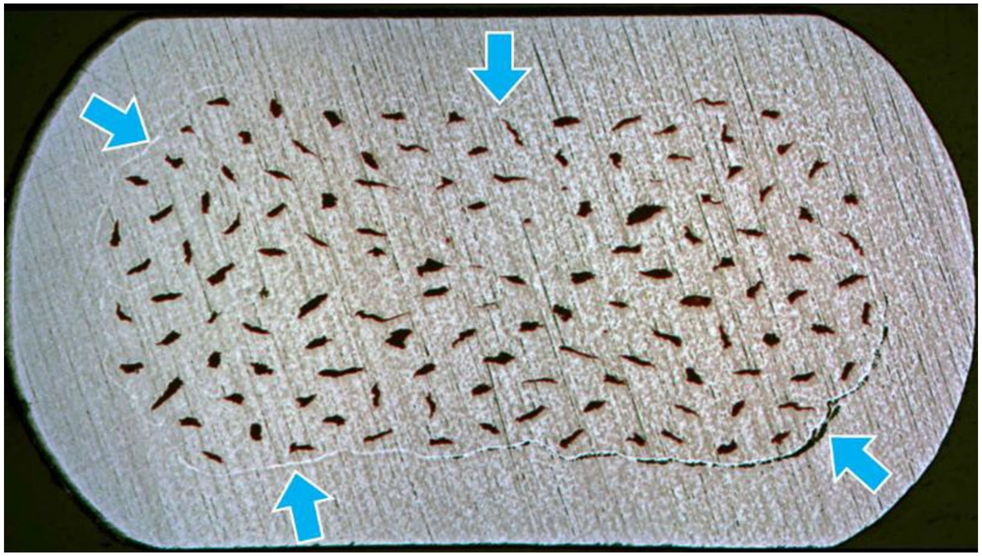
Description of the nonconformities → two types

№ of fuel rod	Microscopic image of cross section with the specimen № *Size of delamination in brackets [micron]*		
15-2			
	№4 (52×171 and 26×271)	№5 (56× 333)	№6 (85×178 and 39×121)
26-2			
	№6 (71×228)	№7 (124×277)	№8 (196×281)

1) There were 4 fuel rods in which delamination was found, the length of which were 2-3 times greater than the acceptable size.

The segments of two of the four rods

2) In one of the tested fuel rods, a violation of the metallurgical adhesion of the cladding with the fuel meat, in the form of delamination, which can be traced along the entire length of the fuel rod, was recorded.



Metallurgical damages of the cladding adhesion to the fuel meat in the form of delamination

NCH #2: delamination – 2/2

- **Justification:** Manufacture justified that the delamination due to the changed manufacturing production technology (detailed justification with analytical results were provided by LUCH)
  - Analyzing this macroscopic discrepancies the calculations showed some thermal effects in the centre of the fuel meat, due to which the meat temperature can increase to 118 °C (at 10 MW) and 156 °C (at 60 MW).
  - To ensure unified interpretation and coherent data in the *Technical Design*, LUCH proposed to amend it with the justification (i.e., correct the wording in the description of the structural condition) and correct the normal boundary condition for the fuel meat temperature at 10 MW from 105 °C to 118 °C and at 60 MW from 146 °C to 156 °C.
- **Verification of the justification:** the impact of the proposed changes was revised by independent expert organization.
  - The revision found that the requested changes in the *Technical Design* do not affect the nuclear and radiation safety of the IVG.1M reactor and extend the permissible limits of operation of WCTC-LEU fuel
  - Thus, the Technical Design was amended with these corrections (**Amendments 2 and 3**).
  - Due to the **Amendments 2 and 3** the revealed nonconformities have been resolved.

WCTC-LEU assemblies' verification – 1/2

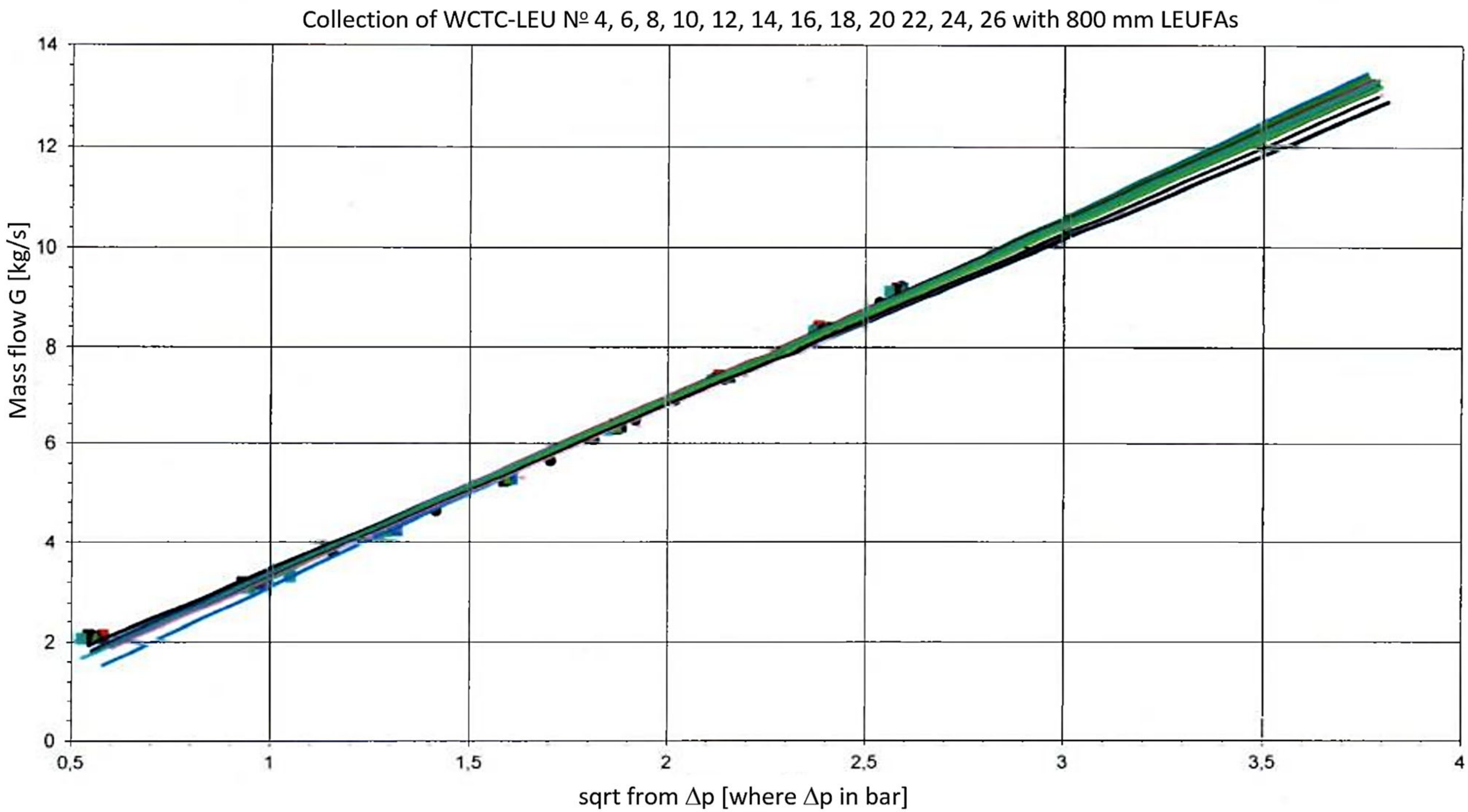
- Subject: the complete 30 pcs WCTC-LEU channels (as defined by sampling)
- Results: they are summarized in the table below.
  - No nonconformities were found
  - Tests were passed successfully

Summary of the WCTC-LEU assemblies' verification

Method	Inspection technique	Requirements	Results
Visual inspection	Inspection of the WCTC-LEU assemblies with the naked eye	Scratch and damage free surface	Signs of corrosion, mechanical damage, cracks, dents were not found. *Passed successfully*
Size check	Inlet size by control gauge	Smooth movement of the control gauge	There were no jamming or distortions *Passed successfully*
Checking tightness and strength of connections	Water-filled channel pressure test at 1.8 MPa for 10 minutes	No pressure drops and water leaking	During the tests, no pressure drops, or water leaks were found. *Passed successfully*
Determination of the hydraulic characteristics of the channel	Determination of the hydraulic characteristic by measurement on a suitably instrumented test loop	1) The function curve of the $G=f(\sqrt{\Delta p})$ fitted to the measurement points is a straight line; and 2) $G=7^{\pm 0.1}$ kg/s at $\Delta p \approx 0.2$ MPa (2 bar).	The results of the measurements of the hydraulic characteristics met the requirements. *Passed successfully*

WCTC-LEU assemblies' verification – 2/2

- The measurement results of the WCTCs with 800 mm long LEU FAs, which, as it can be seen, complied with the requirements, like the 600 mm ones (they are not presented).



Mass flow (G) as a function of the square root (sqrt) of the Δp: G=f(√Δp)

Conclusion – 1/2

- The manufacturer and NNC in their joint final reports, based on the results of
  1) The comprehensive SAT,
  2) The manufacturer's justifications for the test results
  3) The expert opinions confirming the manufacturer's justifications that at the end resulted in three amendments to the *Technical Design*

  commonly justified that WCTC-LEU assemblies delivered for the IVG.1M reactor conversion, passed the SAT in full and without comment.

- The whole implementation of the SAT required nine months of continuous work for the designated experts of the manufacturer and user at the IVG.1M reactor site, which was much longer and more thorough than usual.

- Some words on the ATP:
  - ✓ The SAT was conducted according to a pre-agreed jointly developed ATP, which was a very good nuclear conformance approach.
  - ✓ SAT was overloaded. The SAT covered inspections that can usually be found in the manufacturer's QA/QC documentation or were part of the factory acceptance test (FAT). Of course, the comprehensive, and long lasted SAT was partly understood by the unique design of the WCTC-LEU assemblies.
  - ✓ In retrospect, however, it should be noted that several inspections, especially material thickness measurements and microscopic structural analyses, which are usually part of the FAT, have been included in the SAT. These tests are usually documented in the manufacturer's QA/QC documentation, and in addition, they can be performed more effectively and professionally in the manufacturer's laboratories (screening the QA/QC documents on manufacturing was completely omitted from the SAT).

Conclusion – 2/2

- There were also signs of scepticism from the part of NNC, since the NNC's experts were unable to carry out in-process inspections at the manufacturer's site, and were not able to participate in the FAT due to the pandemic.
- Resolving nonconformities identified in the form of supposed discrepancies during the SAT:
  - ✓ At the end, they have been duly and convincingly justified by the manufacturer and subsequently have been verified by an independent expert team.
  - ✓ As a result, the Technical Design had to be amended three times to establish compliance even in these questioned cases.
  - ✓ These time-consuming justification processes by the manufacturer, and subsequent confirmations by an independent expert team did not strengthen the trust between the parties.
  - ✓ All this, including disputes between the parties over the substantiation of the justifications, could have been avoided if the Technical Design, which served as a reference document, had been jointly updated, especially in the light of the changed manufacturing technology, before the commencement of the fuel manufacturing.

- **Verification by the practice**
  - ✓ Based on the successful SAT, the title of the consignment was transferred from the manufacturer to NNC in January 2022.
  - ✓ NNC started the LEU fuel loading on April 1, 2022 and completed on April 21, 2022.
  - ✓ During the physical start-up in May 2022 the measured nuclear parameters of the LEU fuel fully met the expected ones.