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Changing the World's Energy Future

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# Acceptance test of WCTC with LEU fuel at the IVG.1M research reactor site in Kazakhstan

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## ABSTRACT

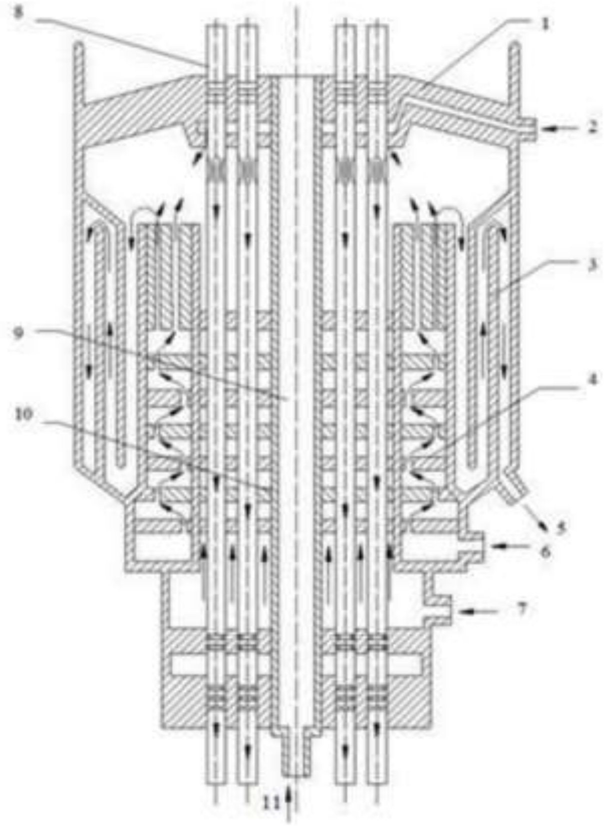
The water-cooled technological channels (WCTC) with low-enriched uranium (LEU) fuel, in the amount required for conversion, were delivered to the IVG.1M site by the manufacturer in February 2021 and thereafter the site acceptance test (SAT) of the WCTCs and the fuel elements started immediately. The paper provides an overview of the SAT conducted between March and November 2021 by the designated experts of the reactor operator and the manufacturer. It includes the introduction of the IVG.1M reactor and its unique WCTCs, and the inspection methodology to verify the conformity of the quality of the LEU fuel with the *Technical Design* (reference document). The paper presents results of the non-destructive and destructive tests, the outcomes of the thermohydraulic measurements, as well as the evaluation and corrective actions (if any), including the amendments (modifications) of the *Technical Design* initiated by the manufacturer based on the test results. Finally, the paper draws conclusions on the effectiveness of the SAT method used, captures consolidated experiential knowledge and shares lessons learned that can be used in general when planning and performing fuel verification.

## INTRODUCTION

Kazakhstan, based on the conversion option studies conducted in cooperation with Russia and the United States since 2010, and then the successful in-pile testing of two special water-cooled technological channels (WCTCs) with low-enriched uranium (LEU) fuel (WCTC-LEU) in 2017 [1], during the IAEA General Conference in 2020, together with the United States confirmed their commitment [2] on working together under the auspicious of the IAEA to eliminate all highly enriched uranium (HEU) in Kazakhstan and to convert of the remaining HEU fuelled IVG.1M research reactor to LEU. The WCTCs with LEU fuel required for the conversion were manufactured by FSU Enterprise “LUCH” (Podolsk, Russian Federation – LUCH), which company was the designer and also the manufacturer of the currently operating WCTCs with HEU fuel (WCTC-HEU) and also the two experimental WCTC-LEU assemblies already tested in 2017. The WCTC-LEU were delivered to the IVG.1M site in February 2021 and thereafter the site acceptance test (SAT) of the fuel elements started immediately by the designated experts of the manufacturer and the reactor operator.

## 1. IVG.1M reactor’s fuel assembly

The IVG.1M reactor can be characterized by both vessel and channel type features. The channel characteristics are provided by the special WCTCs that include nuclear fuel elements. The core scheme of the IVG.1M reactor is shown in *Fig. 1*. From the viewpoint of paper topic, the WCTCs are in the focus that are located vertically in the central part of the core and their length is 4990 mm.




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

*Fig. 1.* IVG.1M reactor’s core scheme with the indication of coolant flow direction

*Fig. 2.* Cartogram of the WCTC location in the IVG.1M reactor’s core

*Fig. 2*, as a cartogram, shows the location of the WCTCs in the reactor core. As it can be seen in the drawing, the total number of channels are 30 and they are in two circles in the core.

The functional and nodal scheme of the WCTC is presented in *Fig 3*. The fuel assembly sleeve is located inside the WCTC capsule (approximately in its middle section where the body diameter of the WCTC is 76 mm) and it contains a package of a set of spiral fuel rods (fuel assembly – FA). 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 (*Fig. 4*). The cladding material of the fuel rods is zirconium alloy E110 on the ends with nickel coating, while the fuel meat is a composition made of zirconium alloy E110 with uranium filaments evenly distributed in it. The uranium-235 enrichment is 19.75% in case of LEU fuel. The length of the fuel rod in case of WCTCs № 1÷18 is 800 mm, while in case of WCTCs № 19÷30 is 600 mm.

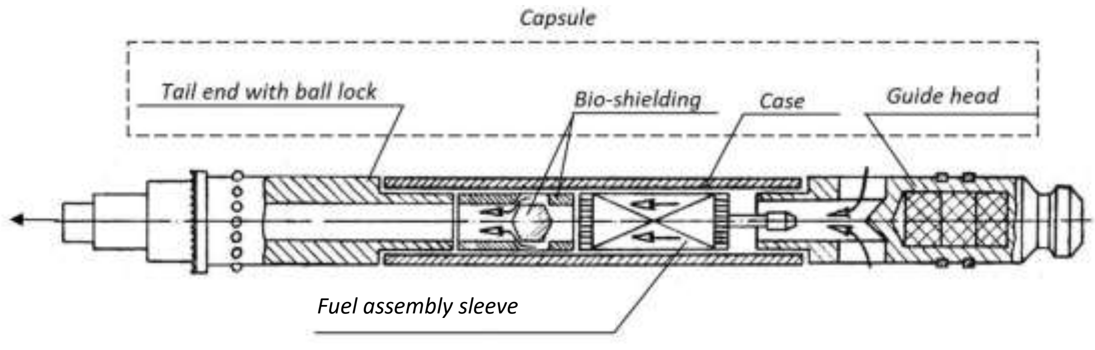
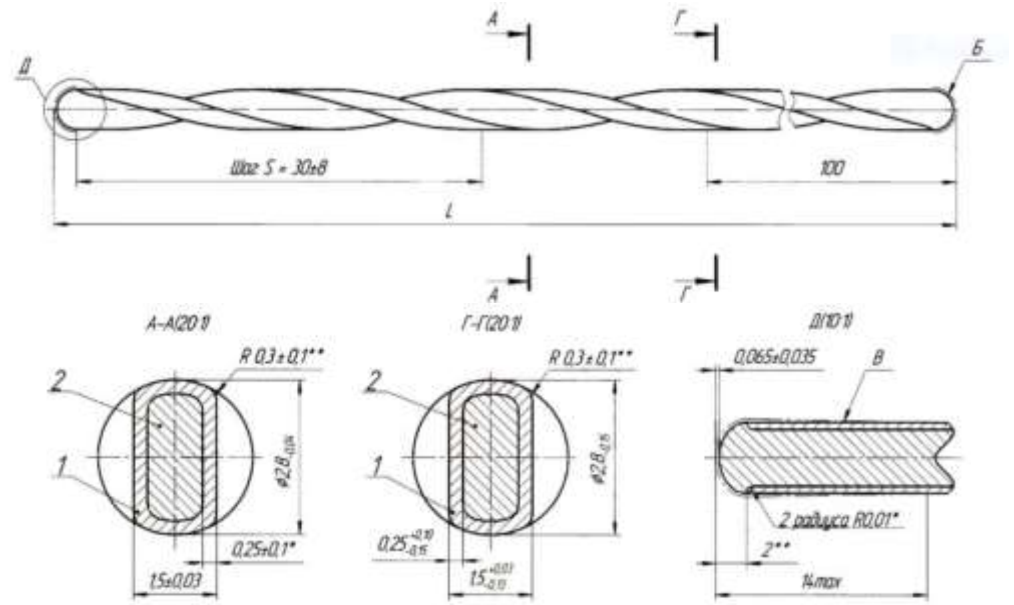



*Fig. 3.* Functional and nodal scheme of the WCTC




1 – fuel cladding (zirconium alloy E110); 2 – fuel meat (zirconium alloy E110 with uranium filaments with an enrichment of 19.75% evenly distributed in it)

*Fig. 4.* Drawing of the fuel rod

## 2. Acceptance Test Programme (ATP)

Based on the in-pile test results of the two WCTC-LEU, made prior to the commencement of the production of the LEU fuel required for the complete conversion of the IVG.1M reactor, the National Nuclear Centre, Kurchatov, Kazakhstan (NNC) as user and LUCH as supplier agreed that the fabrication of the WCTC-LEU will be made according to the original, WCTC-HEU fuel *Technical Design* (reference document) developed by LUCH in the late 1980s for the upgrading of the high temperature gas-cooled IVG.1 reactor that had only been updated for HEU fuel [3].

To check the quality of the WCTC-LEU assemblies and to verify their compliance with the *Technical Design*, an *Acceptance Test Programme* (ATP) [4] was previously developed and adopted jointly. Subject of the ATP is the consignment of the third batch[1] of the WCTC-LEU assemblies delivered within the tripartite contract between LUCH, NNC and BATELLE ENERGY ALLIANCE (United State), that includes 52 pcs replacement fuel rods also[2].

The ATP consists of three main groups of verification test methods:

1) Non-destructive tests;
2) Destructive tests
3) WCTC-LEU assemblies' verification.

### 2.1 Non-destructive tests

The subject of this test was the selected fuel rods. The selection method (sampling) according to the ATP was as follow:

- All the 52 pcs replacement fuel rods for non-destructive tests only
- Max. 5% (20 pcs) of randomly selected fuel rods from two sets of FAs.
- 52 pcs, so called witness rods (2 fuel rods randomly taken out from 26 sets of FAs) for non-destructive and destructive tests.

The methods of the ATP for non-destructive tests were:

- Visual inspection
- Measurement of $\alpha$-particle flux density on the end surfaces of fuel rods

[1] Six WCTC-LEU assemblies with some spare fuel rods were delivered earlier as 1st and 2nd batches.

[2] The replacement rods are used to replace rods (so called witness rods) subjected to destructive testing

– 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)[3]
– Follow-up controls/assessment to validate and verify (V&V) of the justification
– Conclusion (qualification).

## 2.2 Destructive tests

The subject of this test was:

– The same 52 pcs, so called witness rods that were selected as witness fuel rods.

The methods of the ATP for destructive test were:

– 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:

– Summarising findings by test elements
– Verify compliance with the *Technical Design*
– Justification (if needed) and V&V of the justification
– Conclusion (qualification).

As a summary, *Table 1* (bellow) shows the relationships among the test methods, the fuel rods tested and the evaluations, as well as corrective actions to be taken and the follow-up controls to validate their results.

*Table 1.* Summary of the non-destructive and destructive test methods

| Test method | Subject | | | Corrective measures / justifications |
|---|---|---|---|---|
| | Replacement fuel rods (52 pcs) | Random selected fuel rods (20 pcs) | Witness rods (52 pcs) | |
| NON-DESTRUCTIVE TESTS | YES | YES | YES | YES (if needed |
| Evaluation (summarized findings) | YES | YES | YES | YES (if needed) |
| Follow-up control (verification of the results of corrective actions) | YES (if applicable) | YES (if applicable) | | |
| CONCLUSION | | | | |
| DESTRUCTIVE TESTS | | | YES | YES |
| Evaluation (V&V of the justification) | | | YES | YES |
| CONCLUSION | | | | |

## 2.3 WCTC-LEU assemblies' verification

The subject of the verification is the complete 30 pcs WCTC-LEU.

The methods of the ATP for this group are:

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

Evaluation:

– Summarising findings by test elements
– Verify compliance with the *Technical Design*

[3] Corrective action can only be interpreted for non-destructive testing.

– Initiate corrective measures (if needed)[4]
– Follow-up controls to validate the conformity after corrective actions
– Conclusion (qualification)

## 3. Implementation of the SAT

The SAT was conducted between March and November 2021 by the designated experts of the reactor operator and the manufacturer following the implementation instruction of the ATP that was previously developed and adopted jointly [4] and introduced in Section No. 2. The course and results of the non-destructive and destructive tests have been summarized in a Joint Report № 1 [5], while the results of WCTC-LEU assemblies' verification are found in another Joint Report № 2 [6]. These documents are the guiding and source documents of the following three subsections (3.1, 3.2 and 3.3).

### 3.1 Non-destructive tests and results

#### 3.1.1 Selection and preparation of fuel rods

– Selection: the fuel rods intended for testing were selected according to the selection method described in subsection 2.1. The selected witness fuel rods after their non-destructive inspection have become objects of destructive tests.

– Preparation: it was made according to the usual non-destructive test preparation: V&V of the fuel rods' identification; calibration of the equipment used for the tests and measurements were part of the preparation.

#### 3.1.2 Test results

A summary of the non-destructive testing is shown in the *Table 2* below. In Column #5 of *Table 2,* in addition to the results, the discrepancies (Nonconformity highlights) revealed during the given test are highlighted with a serial number. These discrepancies are presented below with the corrective measure initiated, action taken, and the results of follow-up control.

*Table 2.* Summary of the non-destructive testing

| Method | Inspection technique | Purpose | Requirements | Results |
|---|---|---|---|---|
| Visual inspection | Inspection of the rods with the naked eye | Identify visible surface defects | Scratch and damage free surface | Defects in the form of chips and sagging were not revealed. **Nonconformity highlights #1** *Passed successfully* |
| Measurement of $\alpha$-particle density on the end surfaces of fuel rods | Measurement of the fuel rod ends with an $\alpha$-particle sensitive detector. Time for each measurement was 200 seconds. | Verification that the quality requirements for fuel rod cropping and ends coating have been met | Flux density of $\alpha$-particles ≤ 2 counts/s/cm$^2$ (above the background) | The density of $\alpha$-particle flux 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 | Verify that the rod ends are properly coated | Ni-coating thickness ≥30 microns | Compliance of the coatings were confirmed. *Passed successfully* |
| Control of geometric parameters | Parameters to be measured:<br>1) Diameter of the circumscribed circle (DCC),<br>2) Blade thickness,<br>3) Twist pitch and<br>4) Length of fuel rods | Verification of geometric conformity | 1) DCC: $2.8^{-0.04}$ mm<br>2) Blade thickness:$1.5^{\pm0.03}$<br>3) Twist pitch: $30^{\pm8}$<br>4) Length of fuel rods: $600^{-1}$; $800^{-1}$ | The compliance of the measured parameters in generally were confirmed, but after repeating the measurements it was found that a significant part of the fuel rods that passed the additional control didn't correspond to the *Technical Design*. **Nonconformity highlights #2** |
| Determination of surface | Measurement with a contact measuring device that is also | Quantified qualification of surface quality to identify | Ra<0.8 microns that is correspond to three wedge- | The measured roughness parameters don't exceed the permissible limit. |

[4] Corrective action can only be interpreted for non-destructive testing.

| Method | Inspection technique | Purpose | Requirements | Results |
|---|---|---|---|---|
| roughness parameter (Ra)[5] | suitable for measuring the curved surfaces | single atypical protrusions and/or depressions[6] | quality surfaces in mechanical engineering (▽▽▽) | *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. | Checking the material homogeneity | $\rho = 4.80^{\pm 0.25}\ \Omega \cdot cm^{-5}$ | The measured values were in the permissible limit. *Passed successfully* |

### 3.1.3 Revealed nonconformities and/or discrepancies

The revealed nonconformities (and/or discrepancies requiring justification) highlighted in the result column of *Table 2* are:

**1) Nonconformity highlights #1: Deficiencies detected by visual inspection**

First, as exemplar, *Fig. 5* below shows images of fuel rods that have met the requirements.

*Fig. 5.* 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. They are:

– Description of the nonconformities:
  = At one end of a fuel rod, a crack with sharp transitions was observed (*Fig. 6*). Although the surface of the nickel coating appeared to be fissured, it was continuous and no delamination areas were visible. The phenomena was highlighted.

*Fig 6.* Images of the detected non-compliance with the technical requirements of the nickel coating on the lateral surface of the fuel elements

  = At one end of a fuel rod the presence of an influx of nickel was detected. The discrepancies detected are shown in the images below (*Fig. 7*).

[5] Ra value indicates the average surface roughness for the length of the measurement performed, i.e., the average difference between peaks and valleys.

[6] Furthermore, the single atypical protrusions and/or depressions may slightly affect the measured geometric parameters.

*Fig. 7.* Images of the detected non-compliance with the technical requirements of the nickel coating on the lateral surface of the fuel rods

– 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 in terms of the quality of the coating made of nickel, 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 [5].

**2) Nonconformity highlights #2: the DCC does not meet the requirements**

– Description of the nonconformities: significant part of the inspected fuel rods had nonconformity with the *Technical Design*. A large number of nonconformities were caused by the tolerance value of the diameter of the circumscribed circle (DCC) of the fuel rods that was defined in the *Technical Design* as: $2.8_{-0.04}$ mm. An exemplary extract from the data sheet of the measured non-destructive test results is presented in *Table 3*. As it can be seen, the factual DCC are out from the -0.04 mm tolerance (data in Column No. 5 highlighted in red).

*Table 3.* 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 | | | | | | | |
| | $30^{\pm 8}$ | $600^{-1}$; $800^{-1}$ | $1.5^{\pm 0.03}$ | $2.8^{-0.04}$ | >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 |
| 4 | 32 | 599 | 1.50 | 2.76 | 55.5 | 34.3 | 0.71 | 1.01 |
| 5 | 32 | 599 | 1.49 | 2.77 | 37.0 | 31.2 | 0.71 | 1.01 |
| … | … | … | … | … | … | … | … | … |
| 44 | 33 | 799 | 1.49 | 2.76 | 31.11 | 30.51 | 1.32 | 1.43 |
| 45 | 38 | 799 | 1.50 | 2.76 | 54.93 | 33.54 | 1.02 | 0.92 |
| 46 | 35 | 799 | 1.49 | 2.76 | 33.81 | 55.41 | 1.32 | 1.12 |
| 47 | 36 | 799 | 1.50 | 2.77 | 35.34 | 64.77 | 1.22 | 1.02 |
| 48 | 35 | 799 | 1.50 | 2.76 | 31.38 | 34.05 | 1.32 | 0.82 |

*Note: measurement results of five fuel rods with 600 mm and five ones with 800 mm nominal length.*

– Justification: upon NNC's request, LUCH evaluated the discrepancy and considered the possible revision of the *Technical Design* with regard to increasing the tolerance range of the DCC. LUCH made a comprehensive study [7] to justify tolerance change and its extent in the *Technical Design* that covered among others technological, thermal, hydraulic, operability, and safety aspects. It was concluded that the considered issues have been appropriate and justified. Thus, the officially initiated changes were:

= Adjustment of the tolerance for the DCC by the value of "minus 0.1 mm"; [initiated to introduce this change into the *Technical Design*];

= The arithmetic means of the values measured on a 5% random sample (fuel rod) removed from a FA shall be taken [initiated to change the measurement protocol in the ATP].[7]

– V&V of the justification: to assess the impact of the initiation, an independent expert opinion was requested by NNC. The independent expert organization, in its report [8] confirmed the LUCH

[7] The relevant ATP protocol has also been changed accordingly.

results 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.*

## 3.2 Destructive tests and results

### 3.2.1 Preparation of samples

– Selection: object of destructive tests were the witness rods that were selected for non-destructive tests (see Subsection 3.1.1).

– Sample preparation: to prepare fragments, the fuel rods were cropped according to the scheme shown in *Fig. 8.*

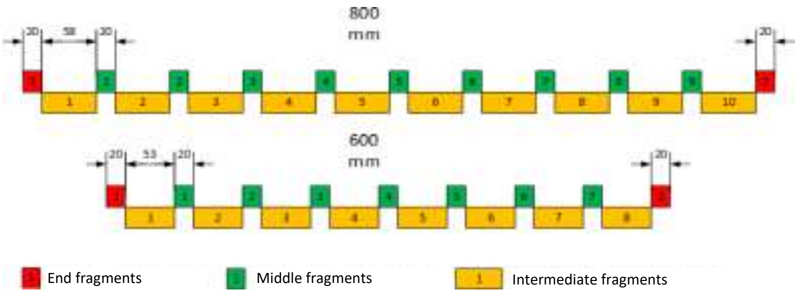



*Fig. 8.* Scheme of cutting up fuel rods

= 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).

### 3.2.2 Test results

The destructive test results are summarized in *Table 4* bellow.

*Table 4.* Summary of the destructive testing

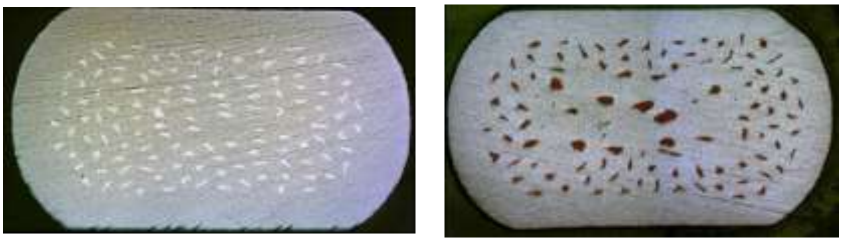
| Method | Inspection technique | Purpose | Requirements | Results |
|---|---|---|---|---|
| Structural analysis of<br>– Cross-section specimens.<br>– end-section specimens | Analysing surface morphology by optical microscope and scanning electron microscope | Verification of structural conformity of fuel meat | 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: $0.25^{\pm 0.1}$ 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 | Verify the uniformity of the U-235 distribution | Uneven distribution up to 12% | The determined uneven distribution of uranium along the length of the fuel elements <4.5%. Relative error <2%.<br>U-235 content was confirmed also<br>*Passed successfully* |

### 3.2.3 Revealed nonconformities and/or discrepancies

The revealed nonconformities (and/or discrepancies requiring justification) highlighted in the result column of the *Table 2* are:

**1) Nonconformity highlights #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 is shown in *Fig. 9*.

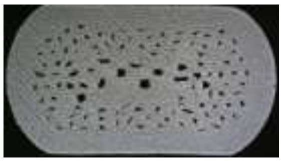


Uniform Uneven distribution

*Fig. 9*. Distribution of uranium filaments in the fuel meat

– Description of the 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 reaches 100 microns along the entire length (see *Table 5*).

*Table 5*. Size distribution of large uranium filaments in 4 defective fuel elements

| **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: LUCH, 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. In addition, due to the shift of uranium along the border with zirconium, it becomes possible for the formation of internal breaks in the uranium filaments, which is inherent in the drawing process. When a rupture or thinning occurs in a uranium filament, as a rule, in the central region of a fuel element, zirconium fills the resulting cavity, and the adjacent filament broadens. The presence of large filaments in the section of a fuel element is explained by an increase in the diameter of the filaments due to the rupture of adjacent filaments [9].

– V&V of the justification: expert opinion was requested for V&V of the justification (see below).

**2) Nonconformity highlights #2: delamination**

– Description of the nonconformities:

  = In the fuel meat there are 4 fuel rods in which delamination was found, the length of which is 2-3 times greater than the acceptable size. As an illustration, images of the segments of two of the four rods are shown in *Fig 10*.

  = 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 (*Fig. 11*). The maximum delamination with a width of up to 25 µm was found in the places where tensile stress occurred at the stage of fuel rod fabrication (flattening).

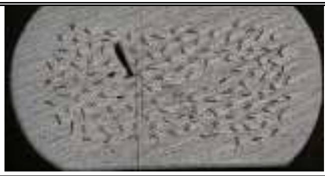
| № of fuel rod | Microscopic image of cross section with the specimen № *Size of delamination in brackets [micron])* | | |
|---|---|---|---|
| 15-2 |  |  |  |
| | №4 (52×171 and 26×271) | №5 (56× 333) | №6 (85×178 and 39×121) |
| 26-2 |  |  |  |
| | №6 (71×228) | №7 (124×277) | №8 (196×281) |

*Fig. 10.* Images of the segments of two of the four fuel rods

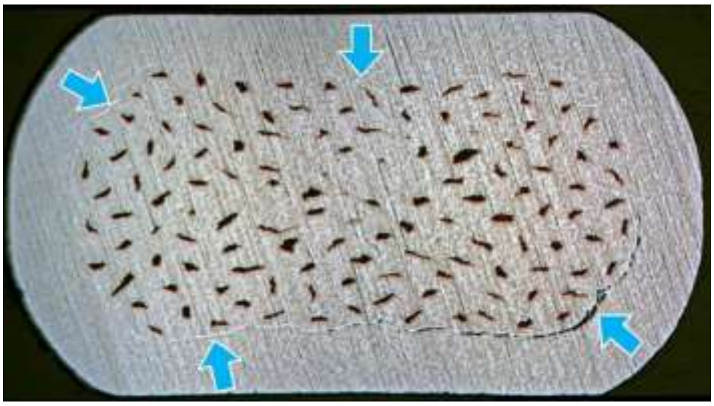


*Fig 11*. Metallurgical damages of the cladding adhesion to the fuel meat in the form of delamination

– Justification: LUCH considers it justified by analysing the macroscopic consequences of the manufacturing technology presented in reference [9], according to which during crimping of a multi-strand wire, local delamination can occur in the body and along the matrix boundary. The calculated analysis of the thermal effect of the maximum stratification, revealed during the incoming inspection, shows that the temperature in the centre of the fuel meat can increase to 118 °C and 156 °C, respectively, at the power of the IVG.1M reactor by 10 MW and 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 [9].

– V&V of the justification. Analysing the proposed changes, the independent expert organization found that the requested changes in the design documentation do not affect the nuclear and radiation safety of the IVG.1M reactor and extend the permissible limits of operation of WCTC-LEU fuel elements [8]. Thus, the *Technical Deign* was amended with these corrections (Amendments 2 and 3).

### 3.3 WCTC-LEU assemblies' verification

The conformity tests were conducted according to the ATP as it is specified in Subsection 2.3. Subject of the verification was all the 30 pcs WCTC-LEU assemblies, 18 pcs of them with 600 mm and 12 pcs with 800 mm length. Summary of the WCTC-LEU assemblies' verification is shown in the *Table 6* below.

*Table 6.* Summary of the WCTC-LEU assemblies' verification

| Method | Inspection technique | Purpose | Requirements | Results |
|---|---|---|---|---|
| Visual inspection | Inspection of the WCTC-LEU assemblies with the naked eye | Identify visible surface defects | Scratch and damage free surface | Signs of corrosion, mechanical damage, cracks, dents were not found<br>*Passed successfully* |
| Size check | Inlet size by control gauge | Verify the inlet size conformity | Smooth movement of the control gauge | There were no jamming or distortions<br>*Passed successfully* |
| Checking tightness and strength of connections | Water-filled channel pressure test at 1.8 MPa for 10 minutes | Verification of the channel tightness and the adequacy of the connections | No pressure drops and water leaking | During the tests, no pressure drops, or water leaks were found.<br>*Passed successfully* |
| Determination of the hydraulic characteristics of the channel | Determination of the hydraulic characteristic by measurement on a suitably instrumented test loop | Verification of the adequacy of the hydraulic resistance of the channels | 1) The function curve of the G=f(√Δp) fitted to the measurement points is a straight line; and<br>2) $G=7^{\pm0.1}$ kg/s at Δp≈6 bar. | The results of the measurements of the hydraulic characteristics met the requirements.<br>*Passed successfully* |

*Fig. 12* shows 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).

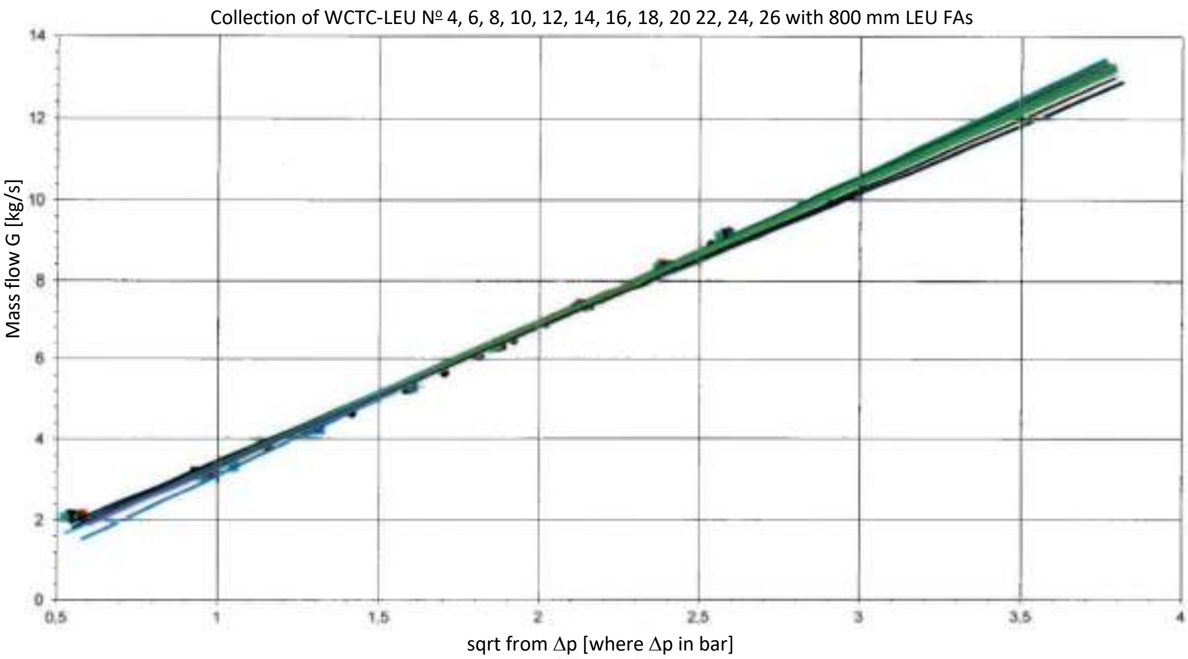



*Fig. 12*. Mass flow (G) as a function of the square root (sqrt) of the Δp: G=f(√Δp)

## CONCLUSION

LUCH and NNC in their joint reports, based on the results of (1) the comprehensive SAT, (2) the manufacturer's justifications for the test results adequacy have been questioned, as well as (3) the expert opinions confirming these 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. Based on the successful SAT, the title of the consignment was transferred from LUCH to NNC in January 2022.

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. The SAT covered inspections that can usually be found in the manufacturer's QA/QC documentation or were part of the factory acceptance test (SAT). Of course, the comprehensive SAT was partly understood by the unique design of the WCTC-LEU assemblies. However, there were also signs of scepticism from the part of NNC, since the NNC's experts were unable to carry out in-process inspections and were not able to participate in the FAT due to the pandemic.

The SAT was conducted according to a pre-agreed jointly developed ATP, which was a very good nuclear conformance approach. 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 on the one hand, and in addition, they can be performed more effectively and professionally in the manufacturer's laboratories, if necessary. Instead of repeated direct tests, it is advisable for the SAT to cover these tests by checking and evaluation the QA/QC documents. It should also be noted that the screening of QA/QC documents on manufacturing had been completely omitted from the SAT, although this assessment is usually an important part of a SAT.

The non-compliances identified in the form of supposed discrepancies during the SAT, at the end 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.

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