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Qualification Process of LEU Fuel – CERCA Type and Conversion Planning for MARIA Research Reactor

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ABSTRACT

The Maria reactor at the National Centre for Nuclear Research in Poland is high-power research reactor that has used HEU fuel manufactured in Russia since it began operation. The IAE has decided to utilize LEU silicide fuel qualified under the RERTR Program and used successfully in many western research reactors for conversion of the MARIA reactor. IAE has contracted with CERCA in France to supply lead test assemblies (LTAs) having a different design, therefore it was necessary to qualify the CERCA fuel assembly for MARIA reactor by direct irradiation of LTAs in the reactor. IAE has completed its analysis and has obtained approvals from the IAE MARIA Safety Committee and from National Atomic Energy Agency of Poland for irradiation testing of the LTAs in MARIA. During August 2009 till January 2011 irradiation testing have been completed, after reaching 40 % and 60 % burnup for LTA-1 and LTA-2 appropriately. After removal from the core and cooling in the storage pool the post irradiation examination were done. Final step of qualification process will be receiving of approval from Regulatory Authority for full-core conversion of MARIA reactor from HEU to LEU. The conversion process will start after delivery of LEU fuel which is planned in June 2012.

1. Introduction

The high-flux research reactor MARIA is operated by the National Centre for Nuclear Research in Poland. MARIA reactor has used HEU fuel manufactured in Russia since it began operation. IAE has contracted with CERCA in France to supply LEU Lead Test Assemblies (LTAs) silicide type.

The fuel assemblies for MARIA reactor differ from the fuel elements U_3Si_2 (fuel plates) that have been used so far and due to the that the implementation of the new fuel in MARIA reactor needs to develop a procedure for qualification of new fuel. The main component of the procedure for qualification of new fuel for MARIA reactor was testing irradiation of two trial fuel assemblies (LTAs) under reactor normal operational conditions [1].

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2. Description of MARIA RR

The high flux research reactor MARIA is a water and beryllium moderated reactor. It is a pool type reactor with graphite reflector and pressurized channels containing concentric tube assemblies of fuel elements. The reactor has been designed with a high degree of flexibility. A vertical cross-section of the reactor pool is shown in Fig.1.

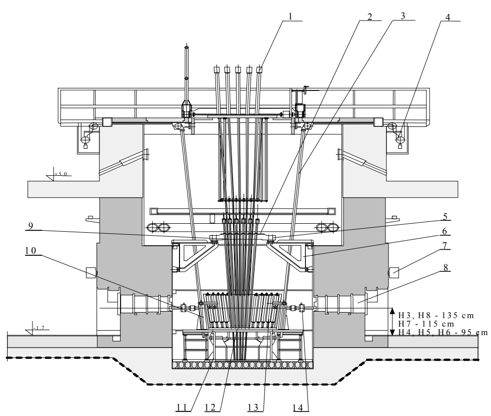

Fig. 1 A vertical cross-section of the reactor pool.

The main characteristics and data of MARIA reactor are as follows:

- nominal power 30 MW(th),
  thermal neutron flux density $4.0 \cdot 10^{14}$ n/cm^{2}s,
- moderator H_2O, beryllium,
- cooling system channel type,
- fuel assemblies:
  - material UO_2-Al alloy
  - enrichment 36%
  - cladding aluminium
  - shape six concentric tubes
  - active length 1000 mm.
- output thermal neutron flux at horizontal channels $3 \div 5 \cdot 10^9$ n/cm^2

3. Generic criteria and technical assumption for MC fuel design

Before formulating the technical assumptions it has been agreed that the procedure for MARIA reactor conversion from HEU to LEU should meet the following conditions:

- Preservation of basic criteria for reactor safety, particularly reactivity, thermal-hydraulic and radiological criteria;
- Providing to maximum extent preservation of basic reactor operational parameters characterising its possibilities as a production and experimental tool;
- Minimalizing, with considering both abovementioned conditions, the additional financial expenditures associated with implementing conversion and reactor operation after completing the conversion process. In particular, it means the necessity of avoidance of serious modifications and upgrading of the existing reactor structure, systems and equipment. These conditions concern:
  - direct financial expenditures on modifications and supplementary components;
  - the reactor operation outages to be forced by such undertakings;

- reactor operation economic parameters such as fuel element price or admissible level of fuel burnup.

In view of the aforementioned generic conditions for the LTA (MC) fuel designing following assumptions have been taken into account:

- MC fuel construction should to maximum extent approximate the MR-5 fuel elements construction. It refers, particularly to the overall dimensions and the manner of fuel element fixing. Admittedly, theoretically it is possible to make the tubes for new fuel by means of extrusion method but this technology for silicide fuel has not been developed so far. It is proposed to manufacture fuel in the shape of three, linked together, bent fuel plates.
- Characteristic feature of the fuel element in MARIA reactor is the two-way coolant flow: between external tubes water flows from top to the bottom and between the internal tubes – from bottom to the top. The tube of the inner diameter ∅ 52 divides both flows and it must be in a leaktight way connected with a separation tube which splits the flow in the fuel channel. The pressure difference between outer and inner fuel tubes can not exceed the value of 0,5 MPa.
- There is a significant difference (up to several dozen of deg.) between the mean temperatures of outer and inner tubes which causes the differences in expansions of the fuel tubes on both sides of the separation tube. This may be the reason of high thermal stresses in the structure of a fuel element.
- Bending of fuel plates containing the U_3Si_2 is a subtle procedure especially in case when the fuel core is distinguishable by a larger hardness than the cladding. In view of that it has been decided to choose five-tubes fuel to avoid to make bending of the tube of smaller diameter than ∅25.
- Due to the necessity of conducting the hydraulic resistance examinations for the MC fuel it was necessary to make a precise fuel element mock-up and to perform the hydraulic examinations before ultimate acceptance of the fuel project..
- The basic thermal-hydraulic parameters affecting the operation of the MC fuel element are enclosed below.

Tabel 1. Initial thermo-hydraulic parameters for the MC fuel element.

Parameter	Value
Coolant – demineralized water	pH 5.5 ÷ 6.5
Coolant inlet temperature	30 ÷ 50 °C
Maximum wall temperature of the fuel element at steady state	boiling is not admissible
Maximum coolant pressure at the header: – supply – offtake	 1.7 MPa 1.1 MPa

Based on the above mentioned technical assumptions the LTAs are made according to the detailing of CERCA, containing fuel element characteristics, manufacturing procedures, description of quality control procedures and acceptance criteria for fuel plates [2].

4. Calculations, safety analysis and measurements for insertion of the LTA's

The calculation analyses and measurements needed in order to obtain approvals needed to insert the LTA's designed by CERCA. The information have been assembled as a set of anexes to the current Safety Analysis Report.

4.1. Core neutronics and reactivity characteristics

The neutronics and core reactivity characteristics for a core with substituted one and two LTAs were compared to the core with HEU fuel in configuration of March 31,2008. These calculations cover: neutron flux distributions, reactivity feedback coefficients and fuel assembly and control rod worth distributions [3][4].The analyzed reactor core neutronics characteristics of cores with 1 or 2 LTAs don't show significant differences with those of reference HEU core.

4.2. Thermal hydraulics, calculation and measurements, limits and transients

The thermal hydraulics calculation covers fuel channel thermal hydraulics, including temperature and coolant flow distributions at steady state under forced flow and natural circulation.
The calculations show that the cladding temperature for MC and MR fuel elements are almost the same, e.g. maximum cladding temperature on the internal surface of the sixth fuel tube is 152°C and 153°C for MR fuel [5][6]. The maximum heat flux on the external wall of the sixth fuel tube for the MC fuel is 2,61 $MW/m^2$and 2,04 MW/m^2 for the MR fuel respectively.
The data acquired from the performed measurements point out that the coefficient of hydraulic resistance for the CERCA MC5D fuel elements exceeds by around 30% the resistance coefficient for the Russian MR6 fuel element.
Safety analyses developed from the performed calculations and measurements confirm the limits and threshold that have been applied so far for the MR fuel beyond the coolant flow rate through the MC fuel element under forced flow conditions.
The boundary levels pertaining the coolant flow rate in individual fuel channel with MC element are:

- warning $G_{k,SO} = 27\ m^3/h$
- emergency $G_{k,SA} = 24\ m^3/h$

Rated flow rate in this fuel channel is: $G_{k,nom} = 30\ m^3/h$.

5. Irradiation testing

The irradiation program of the MC fuel in MARIA reactor covers two phases:

- insertion of 2 MC fuel assemblies into the core and operate them through 12 weeks;
- continuous irradiation them in the core until the final burnup of around 40% and 60% will be achieved which corresponds to the value of burnup 158 MWd and 245 MWd.

The first LTA (MC001) fuel element was inserted in the core at August 10, 2009. The second LTA (MC002) fuel element was inserted into the MARIA core at October 2009 after acceptance by Regulatory Authority of Report of the first phase testing irradiation of MC001. The power generated in the MC001 was systematically increased toward the allowed maximum of 1.8 MW.
There were 5 steps of core position changes of MC fuel:

1. The first MC001 fuel assembly commenced to operate in MARIA reactor for 1 week in position i-5, see Fig. 2, Configuration of reactor core.

2. Then MC001 was moved to high flux position g-6 and operated for one week at the power of 1.6 and was kept as before in position g-6 for 4 weeks and operated on power 1.8 MW,
3. With MC001 still in position g-6 the MC002 was inserted in low flux position i-5,
4. With MC001 still in position g-6 the MC002 was moved in high flux position f-6,
5. With MC001 still in position g-6 and MC002 still in position f-6 the operation was continued for 4 weeks. In that period the MC001 operated at power 1.8 MW.

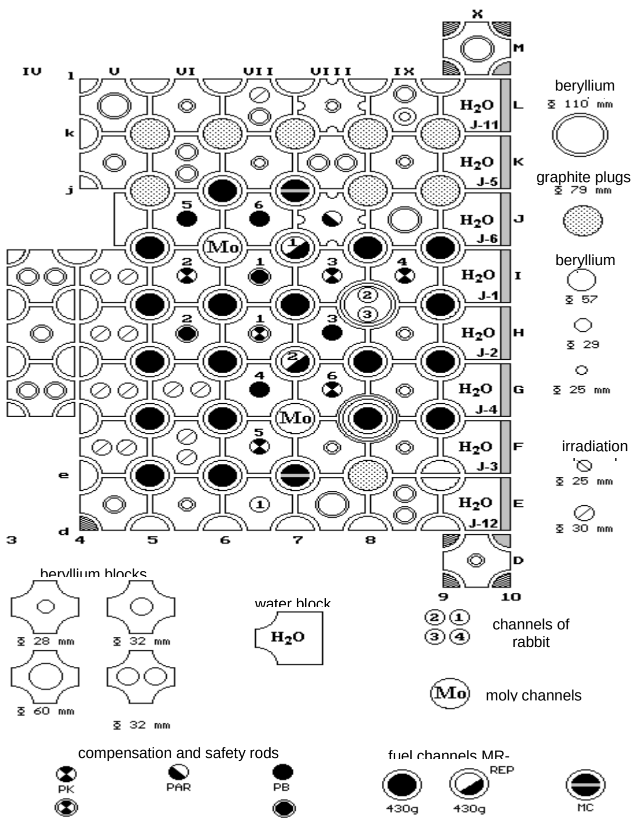

Fig. 2. Configuration of reactor core.

Finally the MC001 occupied mostly position i-7 and MC002 position e-7.

Both MC fuel assemblies were monitored by the normal thermal-hydraulic instruments (i.e., coolant flow rate, temperature rise and outlet temperature). The fuel element power is computed from flow rate and temperature rise. During approaching to the boundary values of burnup the leak-tightness of the MC fuel elements were also monitored by the Fuel Element Integrity Monitoring System (FEIMS) which is based on detecting of delayed neutrons from fuel fission. An increased signal level could indicate a loss of fuel clad integrity. Safety limit measured by the FEIMS is below $1.4 \cdot 10^5$ cpm/1 MW.

6. Conversion planning

Procedure of MARIA reactor conversion from MR fuel into MC fuel includes the following assumptions:

- Exchange of MR fuel on MC fuel will be pursued in a gradual way. From the conversion starting moment at first the spent MR fuel will unloaded from the core whereas the core will be supplemented only by the new MC fuel.
- There will be met all criteria for safe reactor operation, in particular the reactivity limits and the thermalhydraulic and radiological limits. It is to be allowed the diversification of coolant flow rates for MR and MC fuel elements; the rated coolant flow rates through the MR fuel channel are at least 25 m^3/h and in the MC fuel – 30 m^3/h.
- In the course of core conversion the reactor will perform the normal research and production operation. Among other, there will be irradiated uranium plates for production of molibdenum – 99.
- Procedure of the core conversion from MR fuel on the MC fuel has been simulated by means of calculation. In calculation assumed that the fourth operation cycle is a cycle to be aimed for irradiation of uranium plates for production of ^{99}Mo. In Fig. 3 is shown the first core when the conversion process will be initiated.
- It is possible to initiate the conversion process from MR into MC fuel when operating the unmodernized pump system. As it was proved by experiment done for at least two MC fuel elements to be present in the core.
- Each fresh newly loaded MC fuel elements into the core will be continuously monitored by means of the Fuel Element Integrity Monitoring System (FEIMS) during the first operation cycle. The remaining fuel elements will be monitored by the FEIMS in conformity with a standard procedure.
- For the cores with 1, 11 and 21 (complete leading) MC fuel elements there will be performed calibration of absorber rods PK, PAR and PB.

Number of operation cycles

# 1	5	6	7	8	9
j	GR	GR	GR	GR	GR
i	MR 544	MR 3776	MR 997	MR 4814	MR 4329
h	MR 1743	MR 1002	MR 2906	HYDRO	MR 4507
g	MR 2760	MC 0	MR 2920	MR 3047	MR 4197
f	MR 2451	MR 1862	MR 3182	MR 4108	MR 4900
e	MR 3151.55	MR 3318	GR	GR	MR 2855

[MWh]
0
350
700
1050
1400
1750
2100
2450
2800
3150
3500
3850
4200
4550

MR 1320 — Fuel type / Burn up [Mwh] — MC 0

Mo — Molybdenum channel

HYDRO — Hydraulic post

GR — Graphite plug

Be — Beryllium plug

Fig. 3. The first LEU fuel within HEU core.

The complete the fuel core conversion it has been achieved within 43 operation cycles. It will be needed approximately 15 months of fuel power reactor operation. In Fig. 4 is presented the full LEU core.

# 43	5	6	7	8	9
j	GR	GR	GR	GR	GR
i	MC 2761	MC 3372	MC 212	MC 1873	MC 1898
h	MC 4411	MC 4986	MC 4807	HYDRO	MC 2747
g	MC 1057	MC 389	MC 3507	MC 2130	MC 1304
f	MC 3136	MC 1507	MC 3886	MC 3849	MC 233
e	MC 3388.34	MC 3786	GR	GR	Be

Fig. 4 The full LEU core.

7. Conclusion

The CERCA Lead Test Assemblies were succesfully irradiated to the apriori preset values of burnups (ca. 60.26% for MC 001 and ca. 41.10 for MC 002). On achieving the required burnups both test LTAs were unloaded from the core and put into the spent fuel storage pool.
The CERCA LTAs exhibited similar performance during irradiation as the standard Russian manufactured MR-6/36% fuel element which was discharged from the reactor core, after achieving the burnup level 48.4%.
The LTAs indicated high leakproof tightness during test irradiation which meets the nuclear safety criteria formulated by the National Atomic Energy Agency.
The final examination on visual inspection and sipping test of the LTAs were done during period April – October 2011, and results are positive and are shown in presentation [7].
The conversion process of MARIA reactor will start after delivery of LEU fuel in the mid of 2012 and will be completed in the IV quarter of 2013.

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