NEW FUEL IN MARIA RESEARCH REACTOR, PROVIDING BETTER CONDITIONS FOR IRRADIATION IN THE FAST NEUTRON SPECTRUM.

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ABSTRACT

MARIA research reactor was designed as an MTR with individually cooled fuel channels moderated by water and surrounding beryllium blocks. That design gives her excellent irradiation capabilities in thermal neutron spectrum with flux up to $3{\cdot}10^{14}$ n/cm^2/s, but fast neutrons flux is limited to $3{\cdot}10^{13}$ n/cm^2/s. To increase MARIA irradiation capabilities in fast flux new fuel MR-2 design was proposed with place for irradiation target in the middle of the element - that irradiation position would increase fast flux to $1{\cdot}10^{14}$ n/cm^2/s. The fuel will become operational in the first half of 2018. Paper presents MR-2 fuel project together with its thermal hydraulics calculations and new possibilities of targets' irradiation in MARIA reactor.

1. Introduction

New MR-2 fuel bears similarity to MR-6 fuel that, along with MC-5 fuel, is currently used in MARIA reactor in normal operation and can be considered as its modification - instead of six fuel tubes it contains only two plus aluminium flow separator. Removing of inner fuel tubes gave place for irradiation container with the diameter δ=34 mm along the whole active length of the fuel that is 1000 mm, total volume of irradiation equals ~90.8 dm^3. Technical parameters of the fuel are summarized in table 1, cross-section is presented in figure 1. Expected maximum fast neutron flux is $1{\cdot}10^{14}$ n/cm^2/s [1], cadmium shielding was proposed in one of central container variants as a measure to cut out thermal neutrons from the spectrum. Neutron energy spectrums in the irradiation container are presented in Figure 2.

Table 1: Fuel parameters

Total fuel element length [mm]	1315
Fuel plates length [mm]	1000
Enrichment [%]	19.7
Fuel meat type	UO_2
Fast neutron flux [n/cm^2/s]	$1{\cdot}10^{14}$
Irradiation container diameter [mm]	34

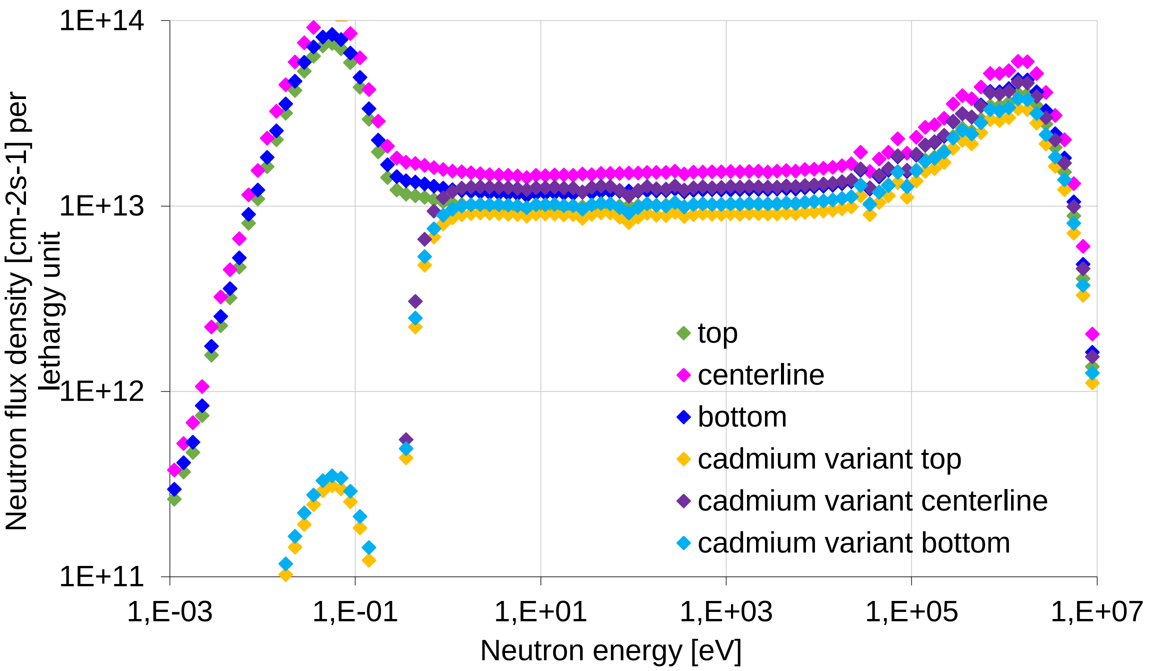

Fig 1: Neutron energy spectrum in central container [1]

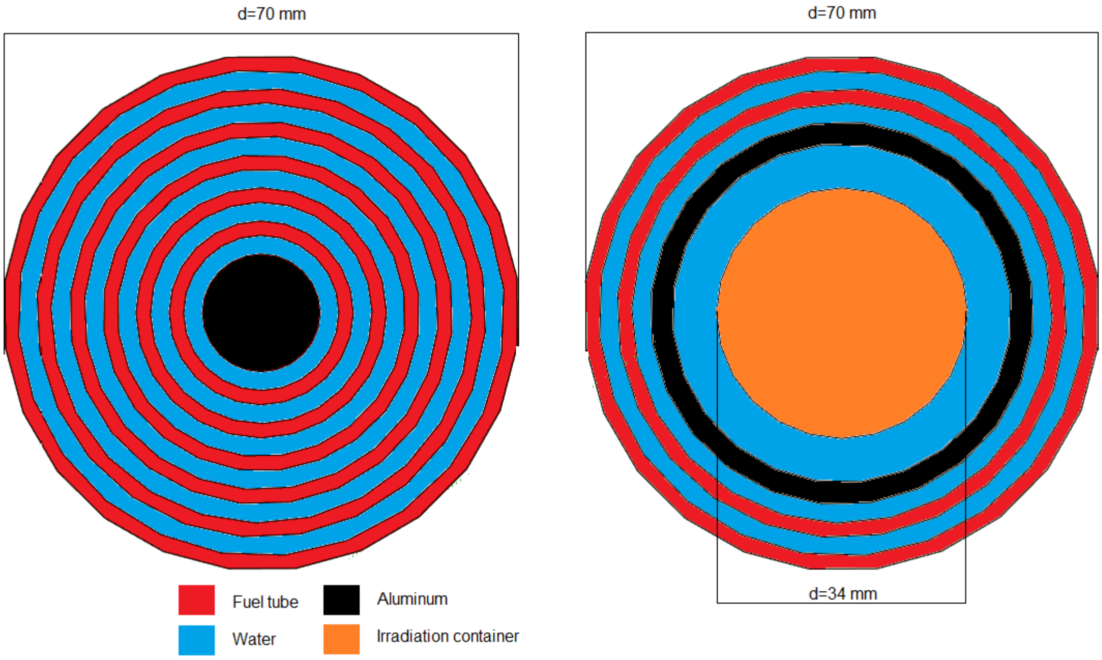

Fig 2: MR-2 and MR-6 fuels comparison

2. Heat transfer calculations

2.1 Theory

For the calculations, Finite Difference Method (FDM) was used in the two-dimensional axisymmetric geometry. In that geometry, heat transfer equation takes form (1) which can be rearranged into finite difference formula. Spatial discretization is presented in equation (2) that can be rearranged into (3), for the temporal discretization, implicit scheme was used (4). Grid nodal notation is presented in the figure 3.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\lambda r\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+\dddot{q}=\rho c_p\frac{\partial T}{\partial t} \tag{1}$$

$$\begin{aligned}&\frac{1}{r_i}\frac{1}{r_{i+1/2}-r_{i+1/2}}\left[\left(\lambda r\frac{\partial T}{\partial r}\right)_{r_{i+1/2}}-\left(\lambda r\frac{\partial T}{\partial r}\right)_{r_{i-1/2}}\right]\\&\qquad+\frac{1}{z_{j+1/2}-z_{j-1/2}}\left[\left(\lambda\frac{\partial T}{\partial z}\right)_{z_{j+1/2}}-\left(\lambda\frac{\partial T}{\partial z}\right)_{z_{j-1/2}}\right]+\dddot{q}=\rho c_p\frac{\partial T}{\partial t}\end{aligned} \tag{2}$$

$$\begin{aligned}&\frac{1}{r_i}\frac{1}{r_{i+1/2}-r_{i+1/2}}\left[\lambda_{i+1/2,j}\cdot r_{i+1/2,j}\frac{T_{i+1,j}-T_{i,j}}{r_{i+1,j}-r_{i,j}}-\lambda_{i-1/2,j}\cdot r_{i-1/2,j}\frac{T_{i,j}-T_{i-1,j}}{r_{i-1,j}-r_{i,j}}\right]\\&\qquad+\frac{1}{z_{j+1/2}-z_{j-1/2}}\left[\lambda_{i,j+1/2}\frac{T_{i,j+1}-T_{i,j}}{z_{j+1/2}-z_j}-\lambda_{i,j-1/2}\frac{T_{i,j}-T_{i-1,j}}{z_j-z_{j+1/2}}\right]+\dddot{q}\\&\qquad=\rho c_p\frac{\partial T}{\partial t}\end{aligned} \tag{3}$$

$$\frac{T^{n+1}-T^n}{\Delta t}=\frac{1}{\rho c_p}\left[F_{i,j}^{n+1}(T,r,z,t\ \ldots)\right] \tag{4}$$

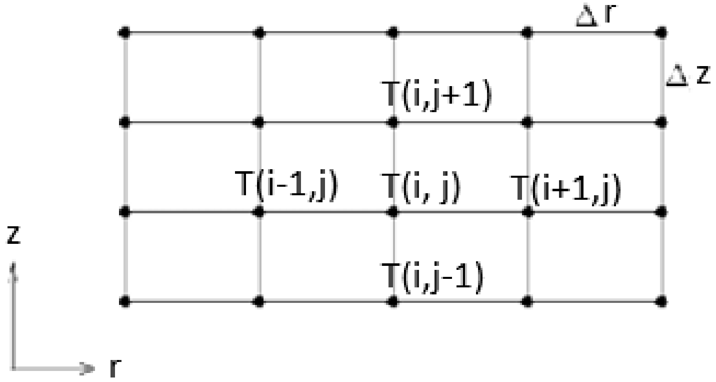

Fig 3: Grid nodal points notation

Two specific spatial nodes are also needed – at the centreline (5) and at the surface that has contact with the flowing fluid (6)

$$\frac{4}{\left(r_{i+1/2}\right)^2}\lambda_{i+1/2,j}\left[T_{i+1,j}-T_{i,j}\right]+\frac{1}{z_{j+1/2}-z_{j-1/2}}\left[\lambda_{i,j+1/2}\frac{T_{i,j+1}-T_{i,j}}{z_{j+1/2}-z_j}-\lambda_{i,j-1/2}\frac{T_{i,j}-T_{i-1,j}}{z_j-z_{j+1/2}}\right]+\dddot{q}=\rho c_p\frac{\partial T}{\partial t} \tag{5}$$

$$\left(\lambda r\frac{\partial T}{\partial r}\right)_{r_{i+1/2}}=h_f\left(T_f-T_{i,j}\right)\cdot r_{i+1/2} \tag{6}$$

Heat transfer coefficient $h_f=\frac{Nu\cdot\lambda}{\delta}$, and Nusselt number is calculated from Gnielinski's correlation. (7) [2]

$$\begin{gathered}Nu=\frac{(f/8)\cdot(Re-1000)\cdot Pr}{1+12.7\cdot(f/8)^{1/2}\cdot\left(Pr^{2/3}-1\right)},\\ f=\left(0.79\cdot ln(Re)-1.64^{-2}\right)\end{gathered} \tag{7}$$

Set of formulas was rewritten as MATLAB code, Gauss-Siedel iteration method was used for the computation.

3. Steady state

Steady state was calculated with the initial parameters summarized in the table 2. Cooling water parameters (density, conductivity, Prandtl number, specific heat and viscosity) were taken from [3] and estimated with fifth degree polynomials

Calculation results showed that the maximum temperature of cladding is located on the outer side of fuel tube nr. 5 and is 114 °C and, maximum heat flux from cladding to fuel is 1.58 MW/m^2. Those hot points are located is located 150 mm down and 30 mm up from the core centreline respectively. Cladding and cooling water temperatures along the fuel length results are presented in the figures 4 and 5 respectively. In figure 5 temperature field in the whole fuel channel is visualised.

Tab 2: Steady state parameters [5]

Reactor thermal power [MW$_{th}$]	25
Fuel meat power [kW$_{th}$]	956
Gamma heating in aluminium [W/g]	10
Coolant flow through channel [m^3/h]	25
Fuel meat heat conductivity [W/m·K]	139-0.03·T
Cladding conductivity [W/m·K]	180
Fuel meat specific heat [J/m^3·K]	$2.26\cdot10^6+10^3\cdot T$
Cladding specific heat [J/m^3·K]	$2.40\cdot10^6+1.2\ 10^3\cdot T$

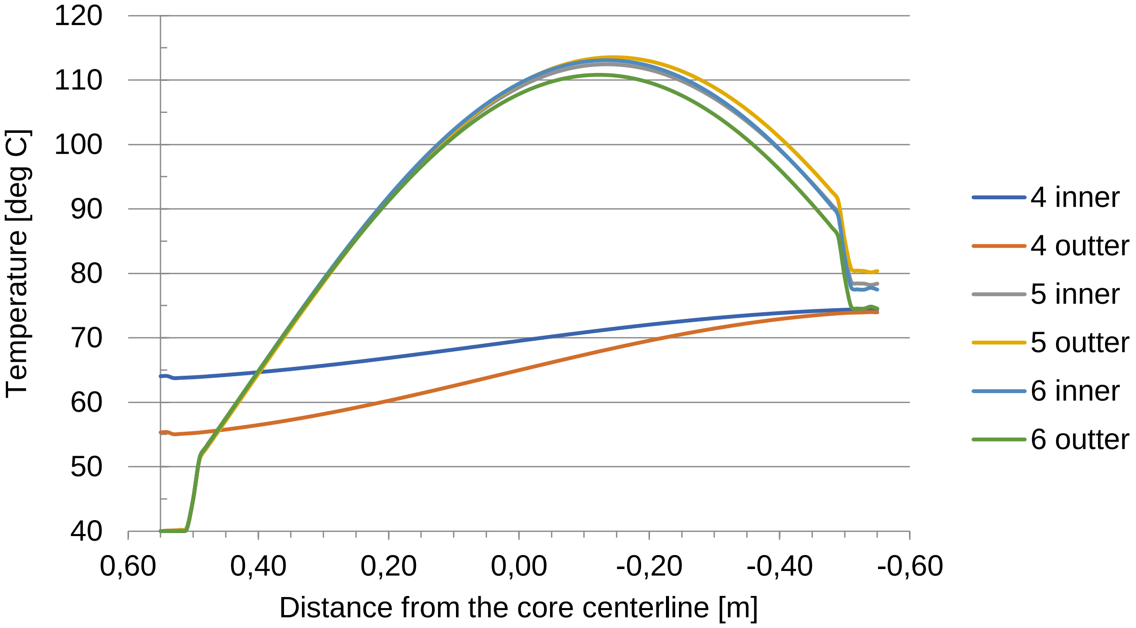

Fig 4 Fuel tubes cladding temperatures in steady state

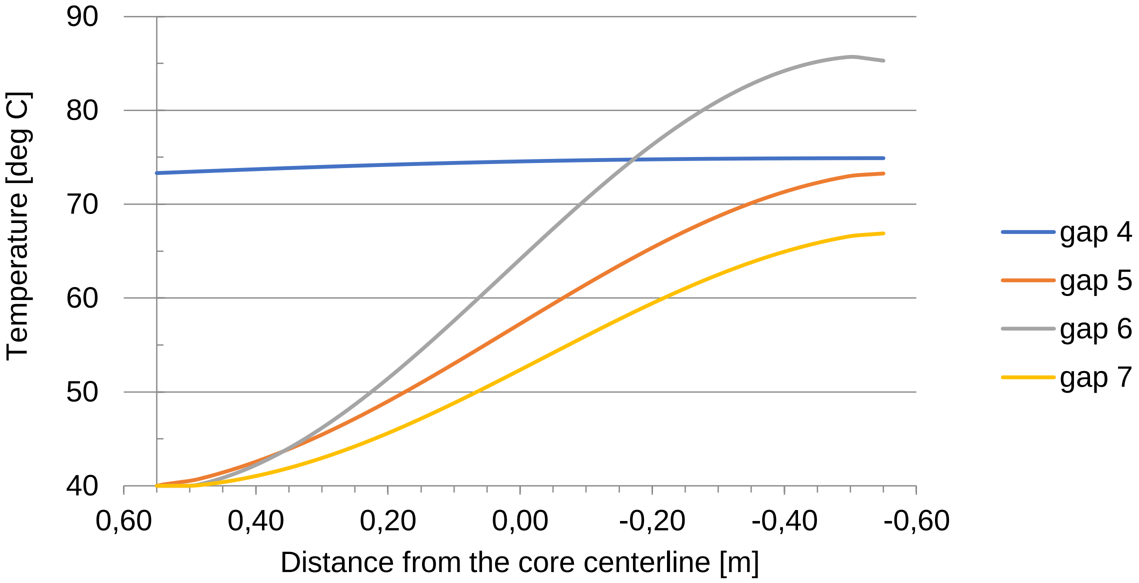

Fig 5: Water temperatures in coolant gaps, steady state

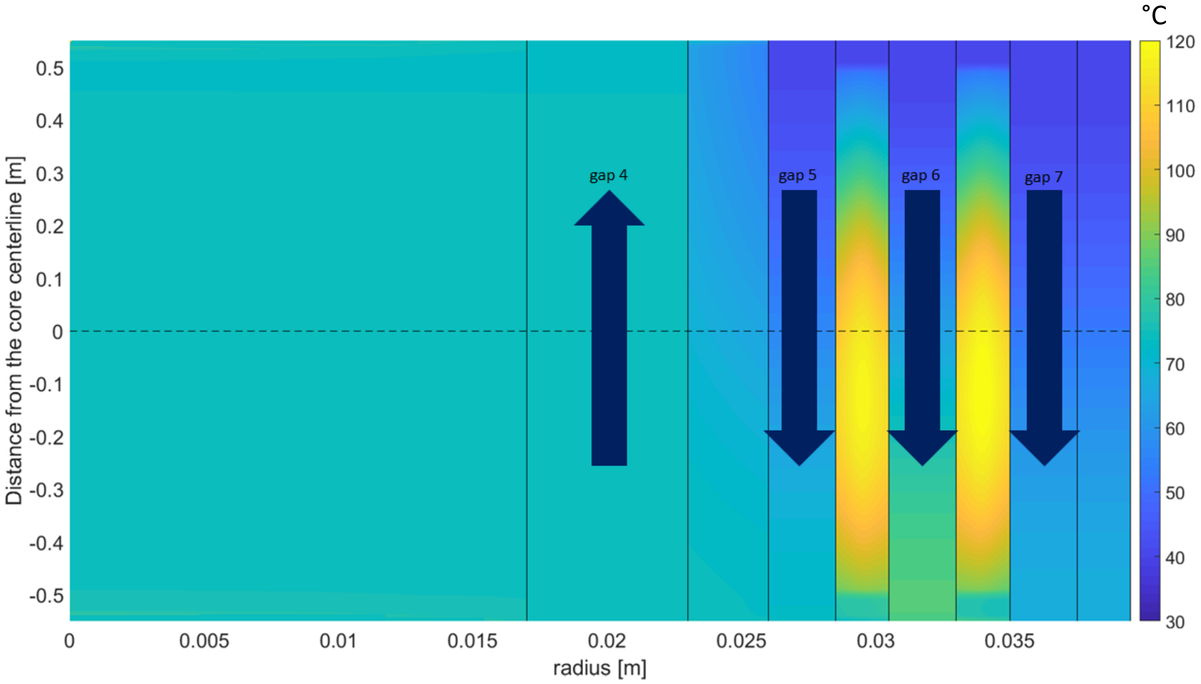

Fig 6: Temperature field in steady state, flow direction marked with arrows

4. Transient.

LOFA scenario was assumed [5]:

1. The coolant flow is decreasing from the nominal value 35 m^3/h, in accordance with the function $G(t)=\frac{G(0)}{1+0.981\cdot t}$
2. SCRAM signal is generated when the flow reaches 80% of its nominal value, with the delay of 150 ms.

3. Control rods worth -5.5 $ of reactivity are fully inserted 600 ms after SCRAM signal, after initial prompt drop, heat starts to decay as a combination of residual fission power and decay heat.
4. Coolant flow stabilizes at the 6 m^3/h, provided by two auxiliary pumps.

For residual fission power and decay heat, formulas (8) and (9) were used respectively [4].

$$P_n = P_{after\,shutdown} \cdot exp\left\{\frac{\ln(2)}{80} \cdot t\right\} \qquad (7)$$

$$P_{\beta+\gamma}=P_0 \cdot 0.1 \cdot \left[(t-t_s)^{-0.2}-(t+10)^{-0.2}+0.87\left(t+2 \cdot 10^7\right)^{-0.2}-\left(t-t_s+2 \cdot 10^7\right)^{-0.2}\right] \qquad (8)$$

As in steady state, hottest cladding point located on the outer side of fuel tube nr. 5, 150 mm down from the core centreline. After flow decrease, both coolant and cladding temperatures started to rise and reached peak values 83 ºC and 132 ºC for times 0.49 s and 0.47 s respectively. After reactor SCRAM both of the temperatures dropped below initial value, but as the flow decrease continued, the second increase was observed: coolant temperature increased to 60 ºC and cladding to 82 ºC at times 5.86 s and 6.84 s respectively. Second increase of temperature was stopped when flow has ceased to drop due to the auxiliary pump activity and after ~5 s period of stabilization, started to decrease slowly due to decay heat exponential decrease. Time series of calculations result is presented in the figure 7.

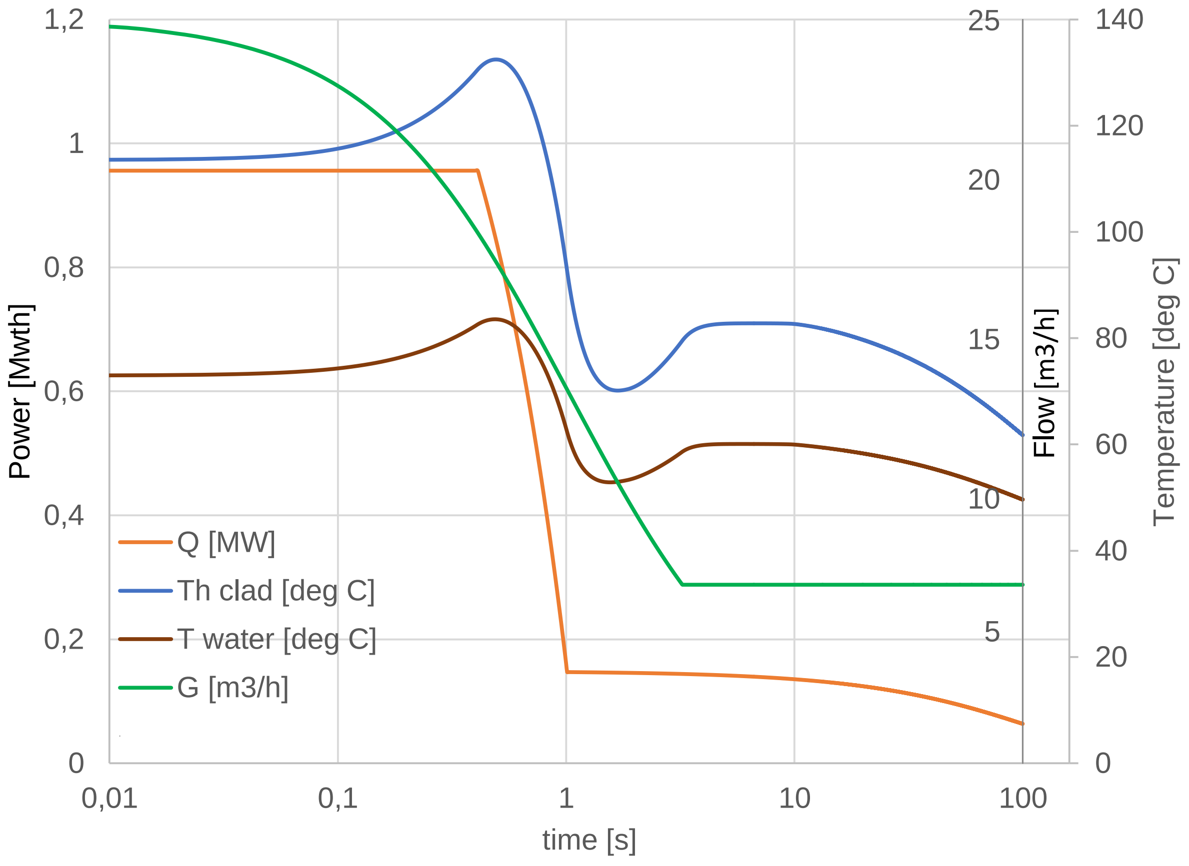

Fig 7: LOFA transient parameters in cladding hot point

5. Summary

Calculations has revealed that new MR-2 fuel can be safely used in MARIA reactor. That opens possibility of new, especially material science, research programmes connected to irradiation in fast neutron spectrum. MR-2 with 34 mm container provides large loading volume of ~90.8 dm^3 for irradiation targets with the maximum expected fast neutron flux fast flux up to $1 \cdot 10^{14}$ $n/cm^2/s$. Two fuel elements of that kind are already in possession of MARIA reactor. Documents submission to the Polish nuclear regulatory body (National Atomic Energy Agency) for license is planned soon, and normal operation is planned to start in 2018.

6. References

[1] R. Prokopowicz, personal communication, email January 2018

[2] Y. A. Çengel, Heat and Mass Transfer: Fundamentals and Applications, McGraw-Hill, New York 2004.

[3] W. Gogół, Wymiana ciepła: tablice i wykresy, Wydawnictwa Politechniki Warszawskiej, Warszawa 1976.

[4] S. Glasstone, Podstawy techniki reaktorów jądrowych, Państwowe Wydawnictwo Naukowe, Warszawa 1958.

[5] K. Pytel et al., MARIA Reactor Safety Report, NCBJ, Otwock – Świerk 2015.