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THERMAL HYDRAULIC DESIGN VERIFICATION OF LEU PLATES IRRADIATION IN RESEARCH REACTOR CORE

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ABSTRACT

Egypt Second Research Reactor (ETRR-2) core was modified to irradiate LEU (Low Enriched Uranium) plates in two irradiation boxes for fission ^{99}Mo production. The in core irradiation has the advantage of using the existing cooling system i.e. no special cooling or irradiation loop is required. Verification of steady state thermal hydraulic design of LEU plates irradiation in ETRR-2 core has been carried out. PARET code and standard correlations were used to calculate various parameters, which include temperature distribution in the core, saturation temperature and Onset of Nucleate Boiling (ONB) temperature, and margins to flow Redistribution (RD), and Departure from Nucleate Boiling (DNB). The calculated parameters are compared with those obtained using TERMIC code and the two results are found in good agreement. The obtained results show that the LEU plates can be irradiated safely in the modified core at a power level of 22 MW without compromising on safety. The results are presented and discussed for the possible LEU plates loading positions in the irradiation boxes.

1. Introduction

ETRR-2 is an open pool research reactor using less than 20% enriched uranium MTR fuel. The reactor went first criticality on November 1997 and was operated satisfactorily at 22MW power level. Its core was modified to irradiate LEU plates for production of fission ^{99}Mo. This modification includes removal of two fuel elements and installation of two irradiation boxes. The modified core (see Fig. 1) comprises of 27 fuel elements, one Co irradiation device, and two irradiation boxes known as Mo production boxes. As shown in Fig. 2, inside Mo production box consists of spacer, two holders where a maximum of six LEU plates can be loaded in each holder, plug, and retaining plug to prevent movement of holders during irradiation. The in core irradiation has the advantage of no special cooling or irradiation loop is required.

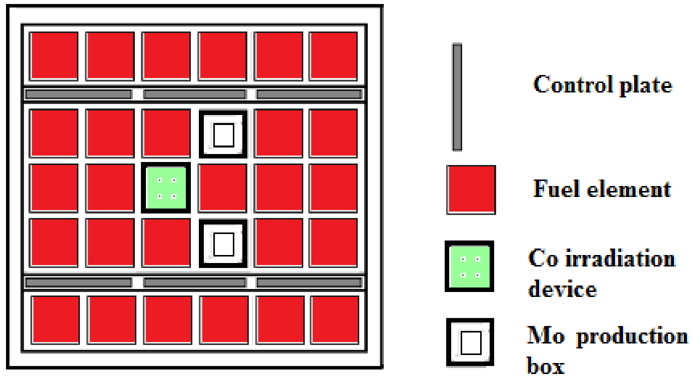

Figure 1: ETRR-2 modified core

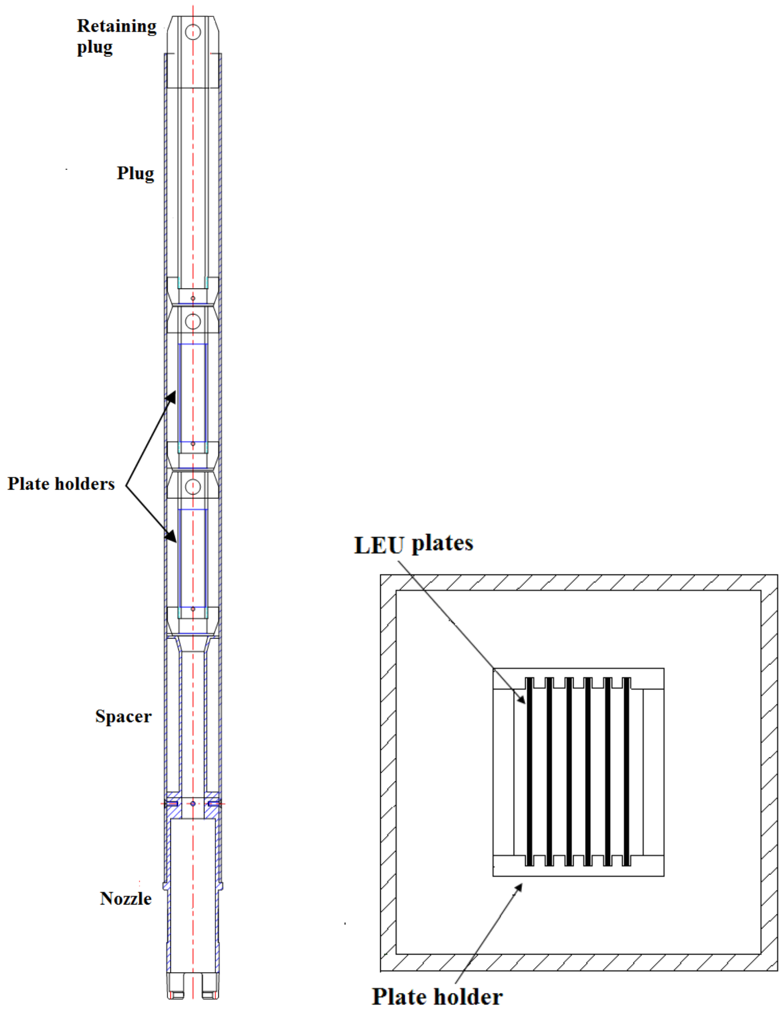

Figure 2: Mo production box

The neutronic calculation has shown that the LEU plate would have an average fission power of 10.5 ± 10 % KW corresponds to the average thermal flux per plate calculated at 22 MW [1]. Validation of this calculated flux is presented in section 2 with description of flux measurement in Mo boxes. Hydraulic calculations were performed using the CAUDVAP code for ETRR-2 modified core. It can calculate the coolant velocity distribution and the pressure drop along parallel channels connected to common inlet and outlet plenums [1]. The validation of this tool and the modelling of the Mo production box were done. A mock-up consists of the irradiation box with the corresponding nozzle and spacer, two plate holders with six dummy plates each, plug and retaining plug was tested in a test loop to provide the measurement of pressure drop values between different points of the box. It was installed inside a test section in vertical position and adapted to represent the geometric conditions of the ETRR-2 core with 27 fuel elements. Tests flow rate is from 3.5 m^3/h to 14.5 m^3/h and temperature varies from 20 ºC to 26 ºC. The pressure was measured at: (i) the box nozzle, (ii) downstream the lower plate holder, (iii) downstream the upper plate holder, (iv) middle point of the plug, and (v) outside the box. The results of the tests were compared with the ones obtained with CAUDVAP code, for a model representing the test section. The comparison shows an agreement of around 10 % between the calculations and the experimental results [1]. A model of the whole ETRR-2 core was developed according to the measurements obtained from the mock-up to verify the proper velocity and flow distribution.

The intent of this work is to perform temperature calculations and verification of the steady state thermal hydraulic design of LEU plates irradiation in Mo boxes. PARET code [2] and standard correlations were used to calculate temperature distribution in the core, saturation temperature and ONB temperature, and heat flux at RD and DNB and the corresponding safety margins. The criterion adopted for the design is the lower between the flow Redistribution Ratio (RDR) and the Departure from Nucleate Boiling Ratio (DNBR) must be ≥ 2. PARET thermal hydraulic calculations and design verification are compared with those in the steady state analysis [1]. The computational tool used for this analysis was TERMIC code, which was developed to perform the thermal hydraulic design of reactor cores with plate type fuel elements. It can be applied to the calculations of the LEU plates. The geometric data and initial conditions adopted for these calculations are given in Table 1 including the calculated power and flow distribution [1, 3].

Table 1: Design parameters of fuel element and LEU plate holder

Design parameter	Fuel element (FE)	LEU plate holder
Plate width	70 mm	32 mm
Plate active width	64 mm	30 mm
Channel thickness	2.7 mm	2.33 mm
Plate active length	800 mm	115 mm
Number of plates	19/FE	6/holder
Number FE/holders	27	2
Power	22 MW/27 FE	10.5 ± 10 % KW/plate
Coolant velocity [1]	5.1 m/s	6.2 m/s
Coolant inlet temperature	40 °C	40 °C- T_{out} of lower holder

[1] Total core flow = 1900 m^3/h

2. Flux measurement

Flux measurement of the LEU plates show that the hottest plate is the outer plate. The radial distribution of the normalized neutron flux is shown in Fig 3 for the six plates in the four possible positions (1, 2, 3 and 4). The distribution is almost the same in the four potions showing a maximum flux in the outer plate no.1. In Fig. 4, the axial shape of the measured flux is shown for the hottest plates. No common shape can be noticed for axial flux distribution. However, the shape can be approximated as a uniform flux having the higher value in upper plate plates compared with the lower plates. The doted line corresponds to the calculated average flux and scattered symbols to the measured flux relative to this calculated flux. It can be seen that the measured flux is below the calculated one + 10 %.

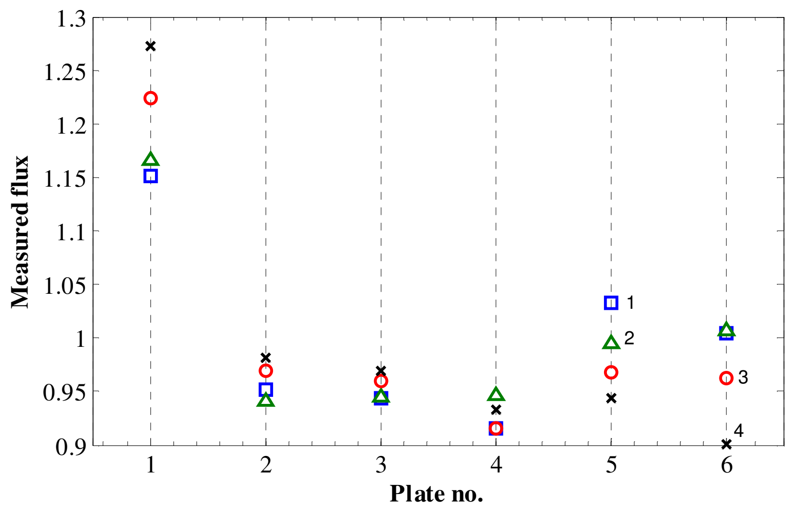

Figure 3: Flux distribution in radial direction

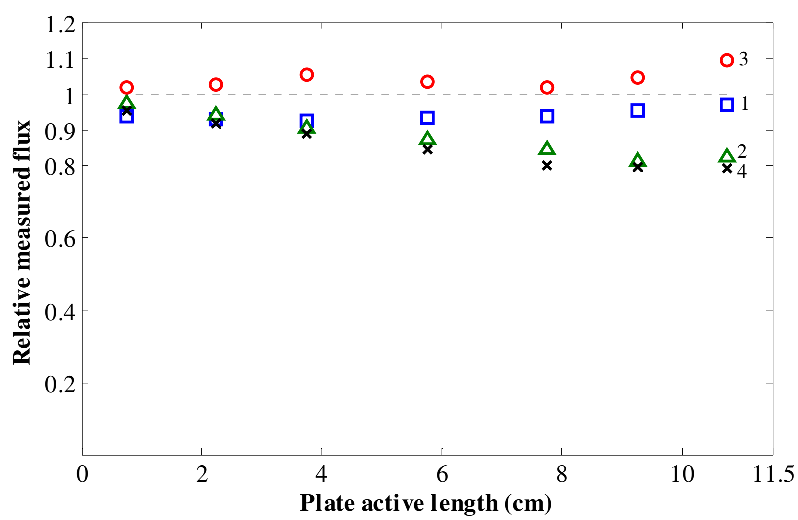

Figure 4: Axial flux distribution of the outer plate

3. Methodology

Thermal hydraulic design verification is placed on plate holders inside the Mo boxes to ensure adequate cooling of the LEU plates and enough margins against the critical phenomena. A single channel model was adopted in the PARET code to have the hot channel calculations of the LEU plate temperature distribution and margins to RD and DNB. The Axial power distribution along the hot channel has been represented by seven axial node points with uniform power distribution. All the calculations have been done with inlet temperature to Mo box equal to the design core inlet temperature 40 ^{o}C and outlet pressure of about 2 bars, which corresponds to the height of water above the upper holder up to low water level of the reactor pool. The coolant inlet temperature to the upper holder is the outlet temperature of the lower holder The PARET code is restricted to a constant inlet coolant temperature of channels and since the Mo production box has two plate holders with two different inlet temperatures, a separate calculation has been done for each holder. Also, the code supports a selection of heat transfer correlations. Dittus and Boelter correlation was selected for the single phase heat transfer to have conservative estimation of the plate clad temperature. It has been assumed that 100 % of the total reactor power is produced in core. COUDVAP code results of velocity distribution and flow rate through coolant channels of the Mo box have been used in PARET inputs. Appropriate correlations for plate type fuel have been used to calculate the margins against critical phenomena.

The calculations have been performed by considering a single hot channel and specifying appropriate engineering hot channel factors. The latter are intended to account for channel area tolerances, uncertainties in calculated parameters, and uncertainties in the measured core power, flow, and inlet temperature [4]. The engineering hot channel factors are applied as four separate components corresponding to: (i) uncertainties in the LEU plate power f_Q, such that $Q_{hc}= Q_{nc}f_Q$, (ii) uncertainties in the channel flow f_m, such that $m_{hc}= m_{nc}/ f_m$, (iii) uncertainties in coolant inlet temperature f_T, such that $T_{hc}= T_{nc}f_T$, and (iv) uncertainties in the heat transfer to the coolant f_h, such that $h_{hc}= h_{nc}/f_h$. In the previous notations hc refers to the hot channel and nc to the nominal channel values for the power (Q), mass flow rate (m), inlet temperature (T), and heat transfer (h). The used engineering factors are summarized in Table 2 [1, 3, 5, 6]. Uncertainties in the measurements and heat transfer coefficient are combined multiplicatively. Nominal or best estimate calculation is obtained with all hot channel factors equal to 1.0.

Table 2: Engineering hot channel factors

Uncertainties	Power	Channel flow	Inlet temperature	Heat transfer
Calculated power/plate	1.10			
Calculated channel flow		1.10		
Channel area		1.10		1.04
Measured core power	1.05			
Measured core flow		1.03		
Measured inlet temperature			1.05	
Heat transfer coefficient				1.15
Total	f_Q =1.15	f_m =1.17	f_T =1.05	f_h =1.20

4. Standard correlations

4.1 Onset of Nucleate Boiling

ONB under low pressure low flow conditions is a measure of the approach to a heat transfer crisis. Bergless and Rohsenow correlation is used for calculating the clad temperature at which ONB occurs [7, 8]:

$$T_{ONB} = T_{sat} + \frac{5}{9}\left(\frac{9.23q}{P^{1.156}}\right)^{\left(\frac{P^{0.0234}}{2.16}\right)}$$

where T_{sat} = saturation temperature, °C, P = local pressure, bar, and q = local heat flux, W/cm^2. The maximum clad temperature T_w is calculated and compared with the onset of nucleate boiling temperature T_{ONB}. If $T_w < T_{ONB}$, margin to ONB exists and the power can be increased.

4.2 Prediction of flow Redistribution

The channel average heat flux $\bar{q}_c$ at onset of flow redistribution can be expressed in terms of velocity, channel geometry, temperatures, and water properties using Whittle and Forgan correlation [7, 8]:

$$\bar{q}_c = R\rho\, C_p \frac{w\, t_w}{w_H\, L_H} v(T_{sat} - T_{in}) \text{ with } R = \frac{1}{1 + \eta \frac{D_H}{L_H}}$$

where

ρ = water density, kg/m^3,
C_p = the heat capacity, J/kg ^{o}C,
v = velocity, m/s,
T_{in} = channel inlet temperature, ^{o}C,
w = fuel plate width, m,
w_H = heated width, m,
t_w = channel thickness (plate separation), m,
L_H = heated length of channel, m,
D_H = heated equivalent diameter of channel = 2 t_w w/(t_w + w_H), and
η = 25 (experimental fit parameter).

$$RDR = R\frac{(T_{sat} - T_{in})}{(T_{out} - T_{in})}$$

The saturation temperature T_{sat} is evaluated at the channel outlet pressure. Outlet temperature T_{out} is calculated in PARET output results.

4.3 Departure from Nucleate Boiling

DNB heat flux is one of the most important issues for the design and the operation of the research reactors. The correlation of Mirshak was found to be suited for prediction of DNB heat flux in low pressure plate fuel reactors [8]:

$$q_{DNB} = 151(1 + 0.1197\, v)[1 + 0.00914(T_{sat} - T_c)](1 + 0.19P)$$

where q_{DNB} = Departure from Nucleate Boiling heat flux ,W/cm^2 and T_c = local coolant temperature, ^{o}C. DNBR is defined as the ratio between the heat flux leading to DNB and the maximum heat flux in the plate.

5. Results

The hot channel temperatures distribution for fuel element (FE) and LEU plates are shown in Fig. 5 at 22 MW core power, 1900 m^3/h core flow and inlet coolant temperature 40.0 ^oC. It is shown that the temperatures of LEU plates are bounded by the FE temperatures. Results of PARET steady state thermal hydraulic analysis are compared with TERMIC results in Table 3.

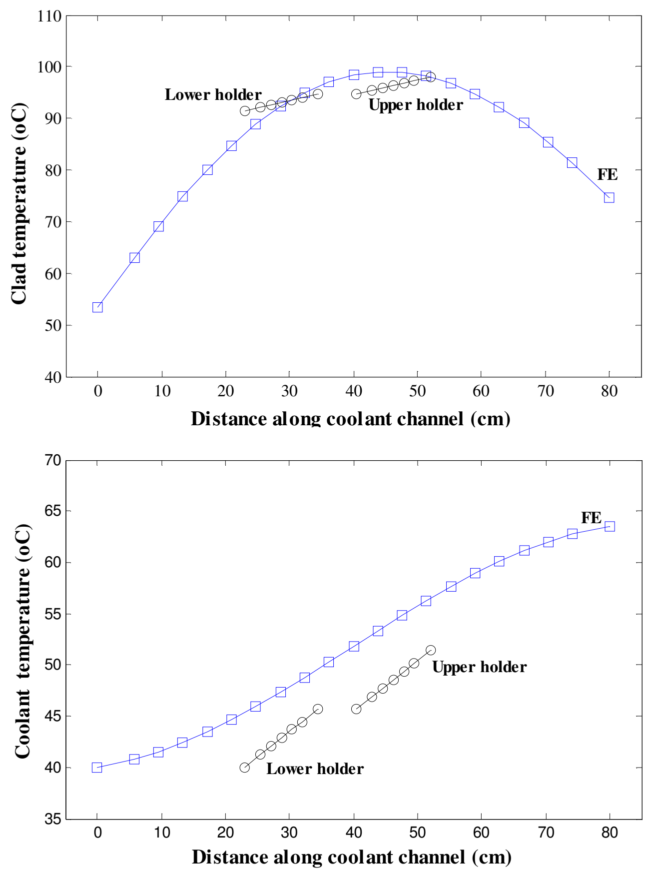

Figure 5 : Clad and coolant temperatures profile for fuel element (FE) and LEU plates

Table 3: Hot channel calculations of LEU pates in Mo production box

Parameter	Lower holder		Upper holder	
	PARET	TERMIC	PARET	TERMIC
Maximum T_w	112 (107.4) ^oC	108 ^oC	116.1 (111.3) ^oC	113 ^oC
$T_{out,}$	49.7 ^oC	49 ^oC	57.4 ^oC	56 ^oC
T_{sat}	119.0 ^oC			
T_{ONB}	132.9 ^oC			
RDR	5.1	5	4.6	3.2
DNBR	3.1	2.7	2.9	2.6

In results table, the temperatures, RDR, and DNBR values computed are incorporating the uncertainties and conservative assumptions. The power is increased to 115 % of the nominal (steady state) value, the channel flow is decreased to about 85 % of the nominal value, and the inlet temperature is increased to 42 ^{o}C. The RDR value of the lower holder plates is closed to TERMIC value because it is assumed that channel outlet pressure is the same as upper plates. The tabulated DNBR are calculated based on Mirshak correlation. It is worth mentioning that a factor of 0.9 is imposed in TERMIC for the DNB heat flux calculations.

The acceptance criterion of maximum clad temperature is to avoid boiling during irradiation. A maximum clad temperature T_w of 116.1^{o}C has been obtained. Incorporating heat transfer uncertainties, $T_w = (116.1-57.4) \times 1.2 + 57.4 = 127.8$ ^{o}C which is below T_{ONB}. Using Sieder and Tate correlation, the maximum T_w (between brackets) is lower than TERMIC calculation.

6. Conclusions

Results show that with assembling Mo production boxes in ETRR-2 core, the LEU plates can be irradiated at 22 MW with a total core flow rate of 1900 m^3/h without compromising on reactor safety. With incorporating all uncertainties factors and conservative assumptions and correlations, the maximum clad temperature at this power level will be below the temperature at which nucleate boiling will commence. The core LEU plates will have sufficient safety margins against onset of flow redistribution and departure from nucleate boiling.

7. References

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