CERCA LEU FUEL ASSEMBLIES TESTING IN MARIA REACTOR – SAFETY ANALYSIS SUMMARY AND TESTING PROGRAM SCOPE

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ABSTRACT

The presented paper contains neutronic and thermal-hydraulic (for steady and unsteady states) calculation results prepared to support annex to Safety Analysis Report for MARIA reactor in order to obtain approval for program of testing low-enriched uranium (LEU) lead test fuel assemblies (LTFA) manufactured by CERCA. This includes presentation of the limits and operational constraints to be in effect during the fuel testing investigations. Also, the scope of testing program (which began in August 2009), including additional measurements and monitoring procedures, is described.

Introduction

According to the overall trends in reactor MARIA an attempt for application of the low enriched (LEU, Low Enriched Uranium) nuclear fuel is being launched. The reactor was primarily designed for operation on high enriched fuel (HEU, High Enriched Uranium) with content of 80% 235 U. In the period 1999-2003 there has been performed a conversion on fuel enriched to 36%. In both cases the Russian MR type fuel was used.

Due to substantial reduction of enrichment under assumption to preserving to maximum degree the physical and thermal-hydraulic parameters of reactor primarily it was foreseen to use U-Mo fuel of highly densed uranium in the fuel ($> 5 g/cm^3$) to be developed in Russian Federation. In 2005 the feasibility study for applying the silicide fuel (U_3Si_2) of 4.8 g/cm^3 density was commenced. Potential supplier of such fuel is the company Areva (CERCA). The proposed fuel has been tested to very high levels of burnup and for the time being is widely used in many research reactors in the world.

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 that the implementation of the new fuel in MARIA reactor needs to developing a procedure for attestation of new fuel assemblies in MARIA reactor. The main component of the procedure for attestation of new fuel for MARIA reactor will be irradiation of two trial fuel assemblies (LTA, Lead Test Assemblies) under reactor normal operational conditions.

The new fuel elements will be denoted further by letters MC to distinguish them from the MR fuel that has been used so far.

Physical Characteristics of the Fuel
- Number of fuel tubes = 5 (6)
- ^{235}U content = 485 g (430 g);
- U_3Si_2 (wt 7.5% Si, 92.5% U) with density 12.2 g/cm^3;
- Uranium density in fuel meat = 4.79 g/cm^3 (2.79 g/cm^3)

Hydraulic Features

Parameter	MR		MC	
Water gaps	Inner	Outer	Inner	Outer
Hydraulic diameter [mm]	5	5	4.49 ÷ 4.71	4.77 ÷ 4.82
Water gaps surface [mm^2]	1005	1496	724	1361
Flow rate through the FA [m^3/h]	25		30	
Average water velocity [m/s]	↑ 6.8	↓ 4.7	↑ 9.2	↓ 5.1
Heat exchange area [m^2]	1.72		1.29	

Hydraulic Characteristics
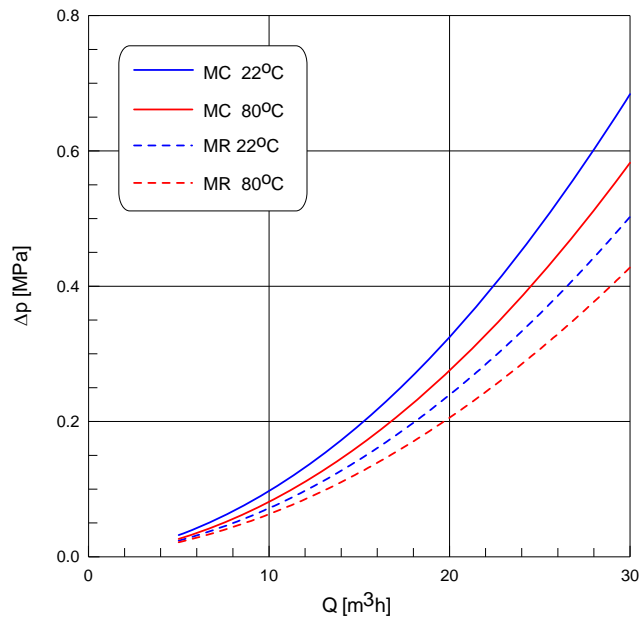
Anticipated pressure drop for LTA irradiation conditions:
- Pressure drop for 22°C:
  - MR (25 m^3/h) – 0.36 MPa
  - MC (30 m^3/h) – 0.68 MPa
- Pressure drop for 80°C:
  - MR (25 m^3/h) – 0.31 MPa
  - MC (30 m^3/h) – 0.58 MPa

MR6 and MC fuel assemblies hydraulic characteristics

LTA Insertion to the MARIA Core

Main assumptions:
- Gradual increase of power loading (start irradiation in peripheral position i-5, control rod PK initially inserted in the vicinity of LTA).

- Observation of the course of power (by means of SAREMA system) and the stability of automatic control operation (ACO).
- Continuous measurements of LTA integrity by means of Fuel Element Integrity Measurement System (FEIMS).
- Periodic sampling of cooling water from LTA (during operation) to perform the spectrometric analyses of FP contamination.

The location of LTAs for full power loading – positions g-6 and f-6 with relatively flat azimuthal loading distribution.
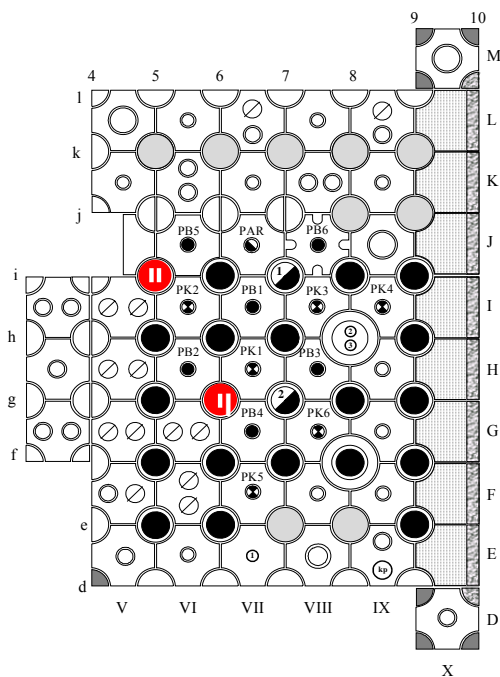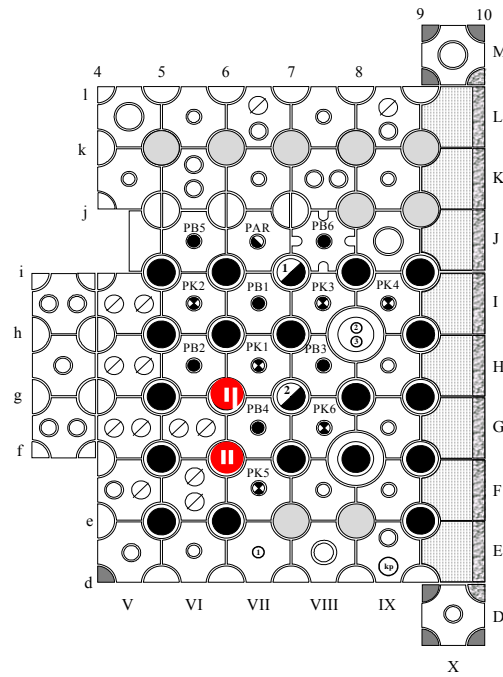
LTA #I to i-5
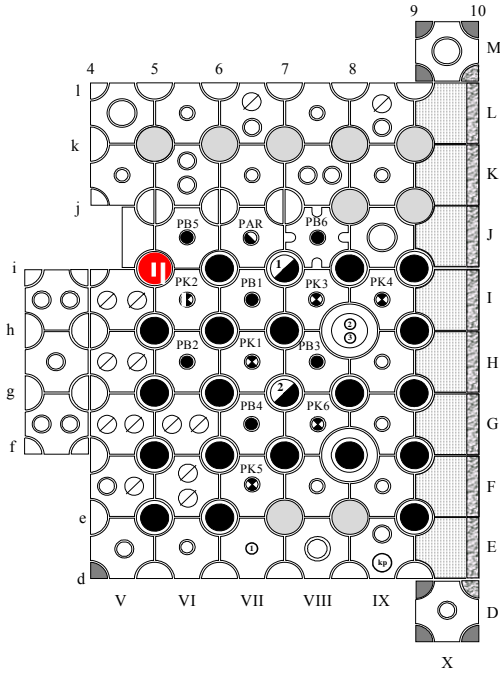
LTA #I to g-6
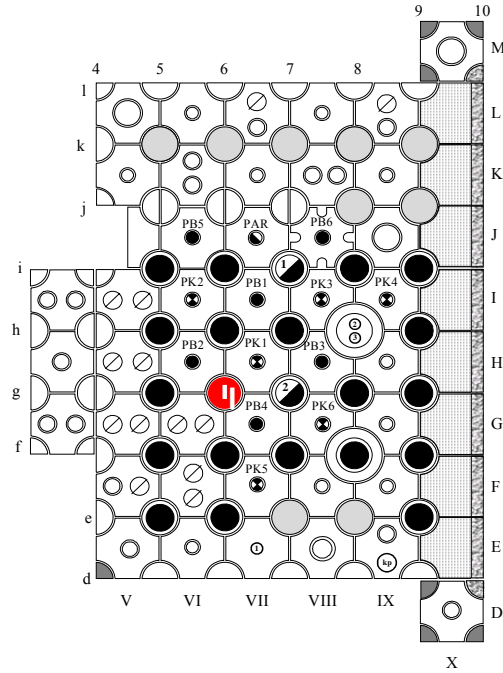
LTA #II to i-5

LTA #II to f-6

Acceptance Criteria for the Testing

Criteria for test suspension:

- Warning thresholds exceeded for LTAs (<90 % flow rate and >110% nominal power);
- Spontaneous (unintentional) power decrease of the reactor or one of LTA (detected by the SAREMA);
- Unstable reactor operation (detected by the ACO)
- Increase of FEIMS signal for LTAs

Test acceptance criteria:

- Burn-up ~40% and ~60% reached
- FEIMS signals below the limit (1.4×10^5 cpm)

Neutronic Analysis

Specific features of MC insertion and irradiation

- Higher ^{235}U content (485 g – MC and 430 g - MR)
- Power peaking to the MC fuel in the initial phase of irradiation at the core centre
- Azimuthal fuel distribution discontinuity due to stiffeners
- Lower enrichment → change of kinetics parameters

Computer codes applied (IAE, ANL)

- WIMS-ANL – cell calculations and libraries
- REBUS, VARI-3D – diffusion codes (reactivity, power distribution, kinetics parameters calculations)
- MCNP – as above
- 4-th May 2009 – reference core

Results: Excess Reactivity
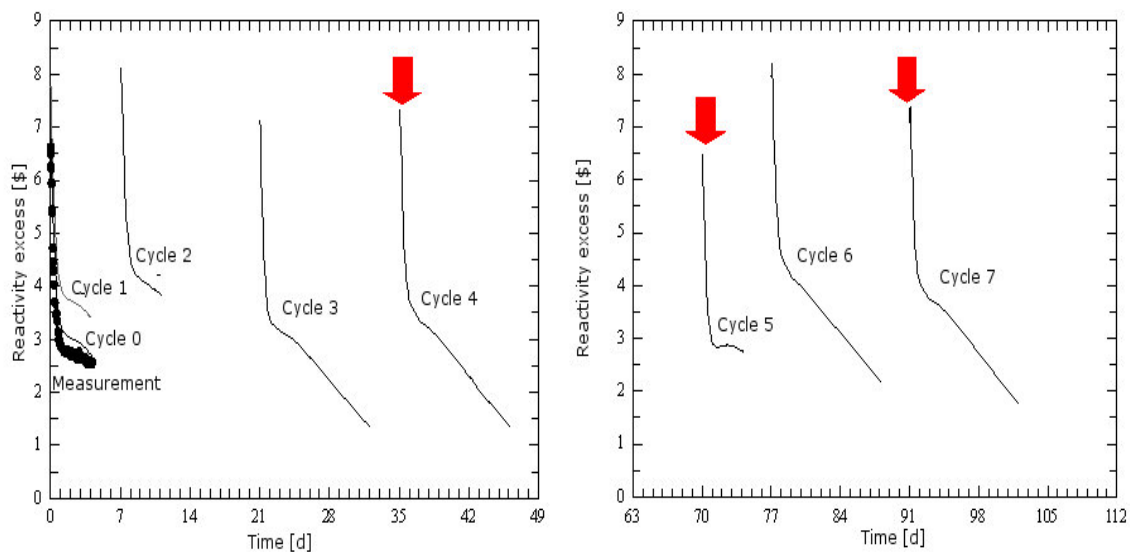
Excess reactivity during first 7 cycles
(Fresh MR fuel required to fill in the excess reactivity ⇓)

Results: Kinetic Parameters & Reactivity Coefficients

Kinetic parameters (uncertainties due to different codes, operation phases e.g. BOC or EOC) – no changes:

- Effective neutron generation time: $L_{eff} = 144 \pm 4$ ms – VARI-3D and REBUS by means of perturbation method
- Effective delayed neutron fraction: $\beta_{eff} = (6.92 \pm 0.02) \cdot 10^{-3}$ – VARI-3D and MCNP

Reactivity coefficients – REBUS (IEA) i MCNP (ANL) – no changes:

- Water temperature: $\alpha_w = -(1.7 \pm 0.3) \cdot 10^{-3}$ $/°C
- Doppler effect: $\alpha_f = -(0.1 \div 0.2) \cdot 10^{-3}$ $/°C
- Void effect: $\alpha_v = -5.6 \cdot 10^{-3}$ $/% void
- Beryllium and pool: $\alpha_{Be} + \alpha_{wp} = +1.9 \cdot 10^{-3}$ $/°C

Results: Azimuthal Power Density Distribution
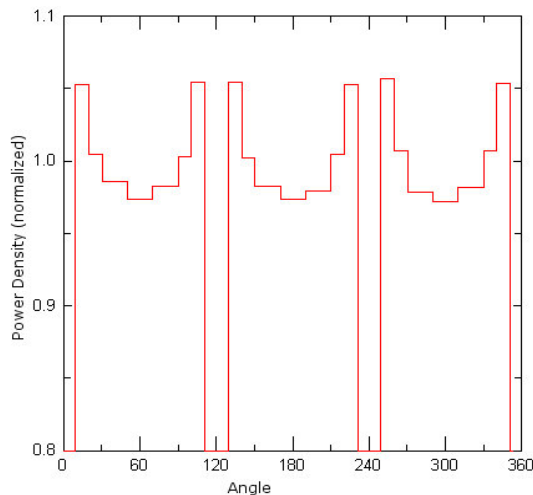
Impact of stiffeners and fuel distribution inhomogeneity, MCNP calculations
Azimuthal power density distribution on the 6-th tube → peaking factor $k_S = 1.06$ (maximum to average)
Local fuel distribution inhomogeneity (±10% for LTAs) does not lead to the heat flux changes exceeding ±10% → uncertainty factor $k_p = 1.1$

Results: Power Distribution Among Tubes
WIMS-ANL calculations

Tube No	Relative Power [%]	
	MR	MC
1	7.5	-
2	10.1	11.0
3	13.2	14.1
4	17.1	18.1
5	22.3	23.8
6	29.8	33.0

Steady-state Thermal-Hydraulics Analysis
- SN code with Dittus-Boelter correlation for the heat exchange coefficients
- ONBR concept involved with Forster-Greif correlation

$$\text{ONBR} = \frac{T_{ONB} - T_{wl}}{T_{k,max} - T_{wl}}$$

- Uncertainty and hot channel factor according to ANL methodology
  - Nominal parameters: $T_k = T_{wl} + \Delta T_w + \Delta T_s$

o   With uncertainties: $T_k = T_{wl} + k_w \Delta T_w + k_q k_\alpha \Delta T_s$

Parameter	Tolerance	k_q	k_w	k_α
Random uncertainties				
Fuel distribution	0.1/0.15	1.1/1.15	1	1
^{235}U loading per tube	0.01/0.03	1.01/1.03	1.005/1.015	1
Channel spacing	0.10	1	1.18	1.04
Azimuthal distribution	0.06	1.06	1.06	1
Power density	0.03	1.03	1.015	1
Systematic uncertainties				
Power measurements	0.02	1.02	1.02	1
Flow rate measurements	0.02	1	1.02	1.016
Heat transfer coefficient	0.10	1	1	1.1
Stiffener effect	0.06/0	1.06/1	1	1
Uncertainty coefficients - random		1.21/1.19	1.24	1.16
Uncertainty coefficients - cumulated		1.31/1.32	1.33/1.34	1.16

Results: Steady-state Thermal-Hydraulics Analysis

- ONBR > 1.2 criterion is more conservative than the saturation temperature
- Operation condition selected for MC fuel: $G_{k,nom}$ = 30 m^3/h

For „warning" parameters i.e. MC element power =   1.98 MW (110%) and flow rate = 27 m^3/h (90%):

- $T_{k,max}$ = 152°C (153°C)
- q_{max} = 2.61 MW/m² (2.04 MW/m²)
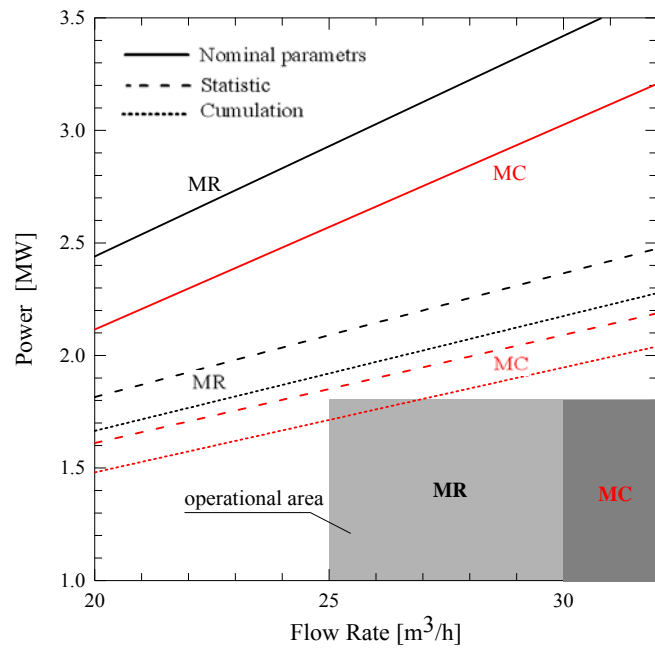
Power vs. Flow Rate plot
(inlet water temperature 45°C and pressure 1.6 MPa)

Transients Thermal-Hydraulics Analysis

Scope:
- Loss of coolant flow – nominal power;
- Positive reactivity insertion and power fluctuation:
    - Slow reactivity insertion 0.04 $/s for a low power;
    - Cold water insertion to low power reactor (fast reactivity insertion);
    - Slow reactivity insertion 0.04 $/s for nominal power;
    - Fast reactivity insertion 4 $/s for nominal power;

Scram characteristics:
- Delay time = 150 ms
- Control (PK) and PAR rods shut-down margin = -2 $ (BOC conditions)
- Safety (PB) rods shut-down margin = -3.5 $ (most reactive PB stuck)

Results: Loss of coolant flow – nominal power
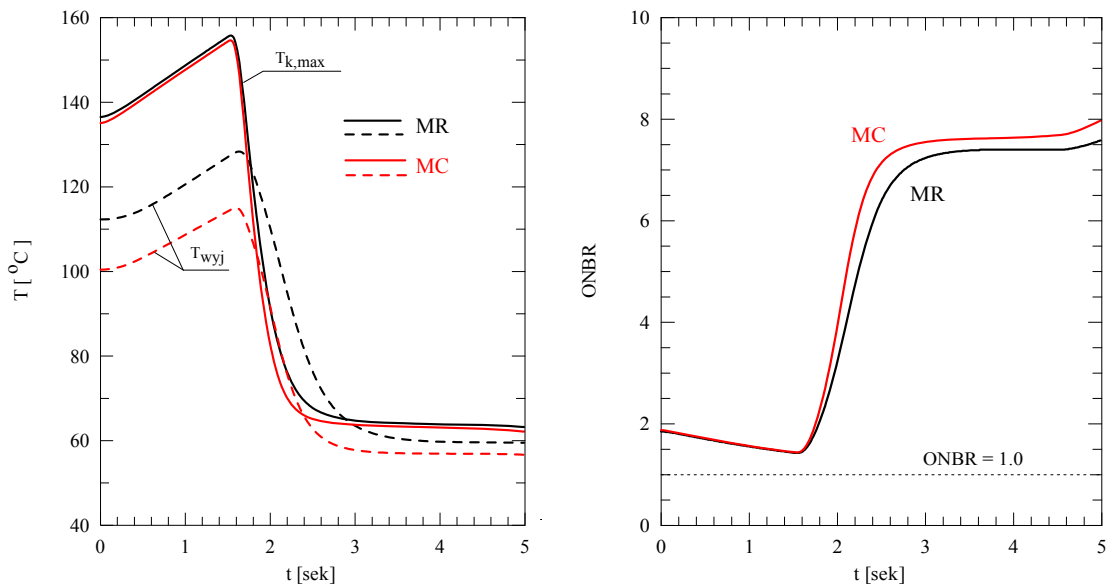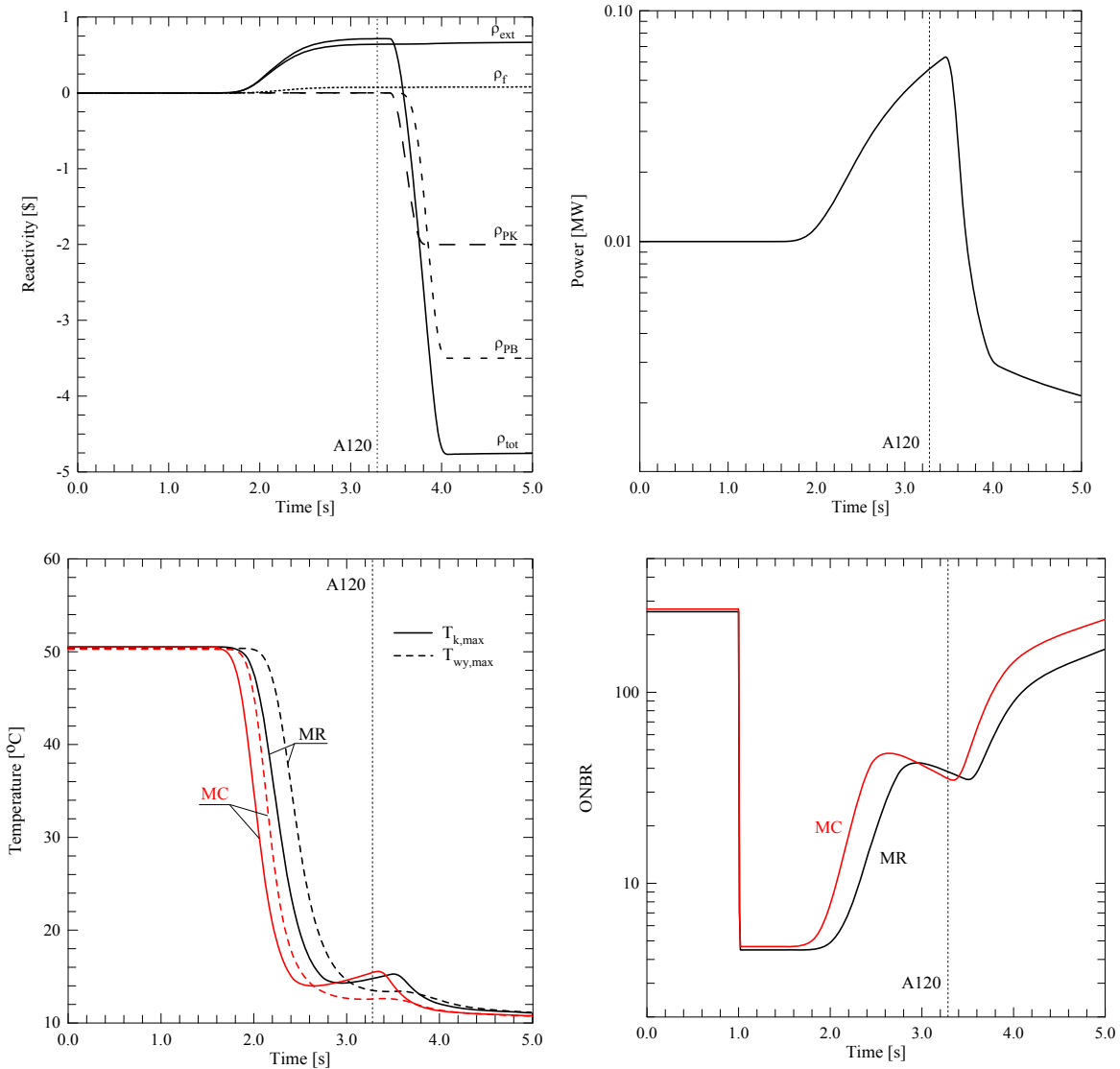
Initial conditions:
- MC fuel element power   1.8 MW
- Initial water temperature   45°C
- Nominal flow rate   30 m^3/h (25 m^3/h)
- Nominal inlet pressure   1.6 MPa

Scram signal – flow rate decrease to 80%

Results: Cold water injection – low power

Initial conditions:

- MC fuel element power   10 kW
- Initial water temperature   50°C
- Nominal flow rate   30 m^3/h (25 m^3/h)
- Nominal inlet pressure   1.6 MPa
- Cold water temperature   10°C
- Reactivity insertion rate   ~1 \$/s (0.68 \$ max)

Scram signal – on power:

- Level: 480% of actual value;
- Delay: 200ms

MC Fuel Melting – Radiological Consequences

Fission products inventory – assumptions:

- MC fuel element power   1.8 MW
- Fuel burn-up   60%

- Release of FP fuel → water   as for MR fuel
- Nominal inlet pressure   1.6 MPa

FP inventory calculation – ORIGEN code (neutron spectral indexes from neutronic calculations).

Ratio of FP content for MC and MR fuel does not exceed 1.3 (for majority of isotopes < 1.1).

Radiological consequences of single MC fuel damage increased by less than 30%

Conclusions

- Steady-state Thermal-Hydraulics analysis confirms, that replacing of the nominal flow through the MR channel (25 m^3/h) by 30 m^3/h for MC fuel restores almost exactly all the thermal parameters (maximum clad temperature and ONBR) but the bulk water temperature (lowered);
- Uncertainty coefficients for both fuels are practically unchanged (valid for LTAs only);
- FP inventory for LTAs shows slightly higher values by max. 30% - no substantial changes in radiological consequences;
- Transient analysis results – all the thermal parameters behavior restored but bulk water temperature. No changes to reactivity and power courses;
- The primary fuel channel circuit is able to provide sufficient flow to 2 LTAs and the entire core after minor rearrangements (e.g. flow reduction through the pressure stabilizer, involving the 3-rd pair of heat exchangers, operation 3 primary pumps)
- The nominal flow rate through the LTAs to be increased to 30 m^3/h and corresponding warning level of 27 m3/h and the scram – 24 m3/h

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