NEUTRONICS AND STEADY-STATE THERMAL HYDRAULICS ANALYSIS FOR THE HEU, MIXED HEU-LEU AND THE FIRST FULL LEU CORES OF WWR-SM REACTOR AT INP AS RUZ

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ABSTRACT

The WWR-SM reactor at the Institute of Nuclear Physics of the Academy of Sciences (INP AS) in Uzbekistan is preparing for the conversion from HEU (36%) fuel to LEU (19.8%) fuel. During this conversion, the HEU fuel assemblies (IRT-3M FA) being discharged at the end of each cycle will be replaced by LEU fuel assemblies (IRT-4M FA); this gradual conversion requires 9 cycles. Conversion to LEU without loss of performance for the present experimental program requires the size of the core to increase from 18 to 20 fuel assemblies and the power of the reactor to increase from 10 to 11 MW. The safety analysis report for this conversion process has been prepared. This paper presents the methods and results for the neutronics analysis (burnup, power distributions and shutdown margin), the steady-state thermal hydraulics analysis and the kinetics parameters for the HEU, all mixed and the first full LEU cores.

Introduction

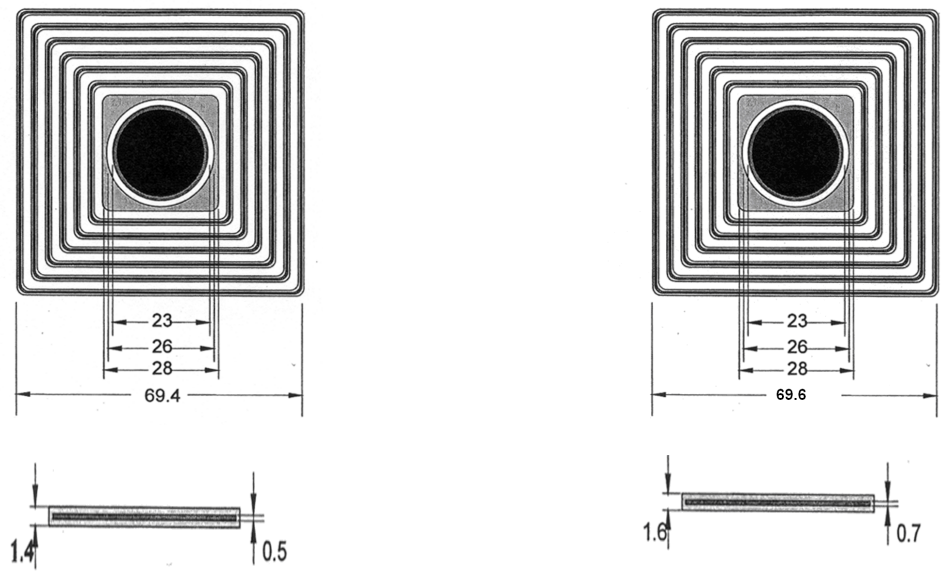
In connection with program realization of restriction distribution of the nuclear weapon transfer of the research reactors using HEU fuel to LEU fuel is carried out. FA IRT-3M with 36 % enrichment on uranium-235 isotope was used in the reactor WWR-SM, INP, Uzbekistan. As new FA with the lowered enrichment in this reactor similar FA IRT-4M will be used, but differing from it by enrichment (19.8 % instead of 36 %).

The purpose of this paper is presentation of parameters of the reactor WWR-SM of INP AS of Uzbekistan at its transfer into use of FA IRT-4M with enrichment of 19.8 % on uranium-235 isotope in core.

The WWR-SM research reactor in Uzbekistan currently uses HEU (36% enrichment) IRT-3M fuel assemblies (6-tubes, UO_2-Al, 2.5 g U/cm^3, 314 g ^{235}U/FA). Previous study has shown that the best LEU fuel for conversion of the WWR-SM reactor in Ulugbek (Uzbekistan) is the IRT-3M UMo dispersion fuel. However, this fuel is not going to be available in the next couple of years. The Institute of Nuclear Physics (INP-UZ) has decided to convert the WWR-SM reactor using presently available IRT-4M oxide LEU fuel, until the IRT-3M UMo LEU fuel is available. To do that without loss of performance for the present experimental program the size of the core will increase to 20 fuel assemblies (FA) and the power of the reactor will increase to 11 MW (instead of 18 FA and 10 MW for the present core). This conversion process will occur over a period of time with partial replacement of IRT-3M HEU fuel with IRT-4M LEU fuel until a fully loaded LEU core is obtained. This paper presents the results for the neutronics analysis (burnup, power distributions and shutdown margin), the steady state thermal hydraulics analysis and the kinetics parameters for the 1st mixed core.

Fuel Assemblies descriptions

Figure 1, shows a horizontal cross section of both the IRT-3M (HEU) [1] and the IRT-4M (LEU) [2] Fuel Assemblies (FA) used in the reactor, and Table 1, presents the parameters of those FA. The two FA are very similar and the major differences are the mass of ^{235}U/FA and the thickness of the fuel meat.



HEU (36 %) IRT-3M LEU (19.8 %) IRT-4M

Figure 1, Cross Section of the 6-tube IRT-3M and IRT-4M Fuel Assembly.

Parameter	6-Tube IRT-3M	6-Tube IRT-4M
Dispersant	UO_2-Al	UO_2-Al
Wt. % ^{235}U	36.0	19.7
$(gU/cm^3)_{meat}$	2.5	2.8
VF^D, %	28.5	31.7
^{235}U/FA, g	309	266
H_{meat}, cm	60	60
T_{meat}, mm	0.50	0.70
T_{clad}, mm	0.45	0.45
$T_{coolant}$, mm	2.05	1.85
Vol_{meat}, cm^3	342	481
Max. Clad Temp., °C	100	98

Table 1, Fuel Assembly Parameters.

Methods and codes used

The WIMS-ANL [3] code was used to generate the 2-group cross sections required by the burnup code IRT-2D [4]. The IRT-2D code was then used to perform cycle-by-cycle burnup analysis. The fuel compositions generated in the burnup analysis were used in a detailed model to be used in the MCNP4C [5] code. This MCNP model was used to perform all the steady state neutronics analysis which provided the detailed power densities and kinetics parameters required for the steady state thermal hydraulics analysis and for the transient analysis.

The steady-state thermal-hydraulics analysis were performed using the PLTEMP code [6] with power fractions obtained with MCNP4C.

Full HEU (18 IRT-3M) and 1st mixed (16 IRT-3M and 4 IRT-4M) cores

The ending of cycle loading of WWR-SM reactor with 18 IRT-3M FAs with 36% fuel enrichment and FA shuffling to get 1st mixed core is shown on the Figure 2, .

230 **47.88** **IRT-3M** 316,2	Number of FA **^{235}U burnup, %** **Fuel type** Initial weight of ^{235}U, g

	2	3	4	5	6	7
6		**230** **47.88** **IRT-3M** **316,2**	**228** **58.73** **IRT-3M** **314,0**	**233** **30.27** **IRT-3M** **314**	**225** **55.60** **IRT-3M** **315,8**	
5	**222** **67.72** **IRT-3M** **315,2**	**236** **19.19** **IRT-3M** **313,8**	**237** **8.12** **IRT-3M** **314,8**	**192** **8.58** **IRT-3M** **300,0**	**231** **42.68** **IRT-3M** **314,8**	
4		**232** **41.01** **IRT-3M** **314.9**	**239** **8.16** **IRT-3M** **313,0**	**238** **8.20** **IRT-3M** **313,3**	**235** **19.84** **IRT-3M** **314,00**	**221** **66.93** **IRT-3M** **313,3**
3		**226** **58.12** **IRT-3M** **316,6**	**234** **31.14** **IRT-3M** **312,5**	**227** **57.75** **IRT-3M** **315,8**	**229** **52.72** **IRT-3M** **313,8**	

Figure 2, Full HEU core with 18 IR-3M FA / end of cycle.

First mixed core of WWR-SM reactor with 16 IRT-3M HEU FAs and 4 IRT-4M LEU FAs is shown on Figure 3, .

	2	3	4	5	6	7
6		230 **47.88** **IRT-3M** 316,2	237 **8.12** **IRT-3M** 314,8	233 **30.27** **IRT-3M** 314,0	192 **8.58** **IRT-3M** **300,0**	
5	228 **58.73** **IRT-3M** 314,0	236 **19.19** **IRT-3M** 313,8	**1M** **00.00** **IRT-4M** 264,0	**2M** **00.00** **IRT-4M** 264,0	231 **42.68** **IRT-3M** 314,8	225 **55.60** **IRT-3M** 315,8
4	226 **58.12** **IRT-3M** 316,6	232 **41.01** **IRT-3M** 314,9	**3M** **00.00** **IRT-4M** 264,0	**4M** **00.00** **IRT-4M** 264,0	235 **19.84** **IRT-3M** 314,0	227 **57.75** **IRT-3M** 315,8
3		239 **8.16** **IRT-3M** **313,0**	234 **31.14** **IRT-3M** 312,5	238 **8.20** **IRT-3M** 313,3	229 **52.72** **IRT-3M** 313,8	

Figure 3, 1st mixed core / beginning of cycle

Shutdown Margin

The WWR-SM reactor criterion for the shutdown margin states that the reactor must be at least 1.0 % sub-critical with all the shim rods and the automatic regulating rod fully inserted into the core. Using this condition the shutdown margin was determined for the cores analyzed and the results presented in Table 2, show that all the cores meet the shutdown margin criterion without any problem.

Core Configuration	Shutdown Margin (Reactivity, %)
18 IRT-3M FA	-8.1
16 IRT-3M / 4 IRT-4M FA, 1st mixed core	-5.5
14 IRT-3M / 6 IRT-4M FA, 2nd mixed core	-6.0
12 IRT-3M / 8 IRT-4M FA, 3rd mixed core	-6.1
10 IRT-3M / 10 IRT-4M FA, 4th mixed core	-6.3
8 IRT-3M / 12 IRT-4M FA, 5th mixed core	-6.8
6 IRT-3M / 14 IRT-4M FA, 6th mixed core	-7.2
4 IRT-3M / 16 IRT-4M FA, 7th mixed core	-7.6
2 IRT-3M / 18 IRT-4M FA, 8th mixed core	-7.8
20 IRT-4M FA, full LEU core	-7.8

Table 2, Shutdown Margin (uncertainty less than 0.5 %)

Control rods reactivity worth

To have a smooth transition from the HEU core to the LEU core it is desired that the worth of the control rods do not change much as the core changes. Small changes in the worth of the control rods are also desired from the viewpoint of the possible transients caused by failures in the control rods mechanism. The reactivity worth of the control rods for the HEU core, and for all mixed and full LEU core are presented in Table 3, . Experimental device influence on efficiency of RCPS rods is insignificant.

	18 IRT-3M Full HEU	**16 IRT-3M/ 4 IRT-4M 1st mixed %**	**14 IRT-3M/ 6 IRT-4M 2nd mixed %**	**12 IRT-3M/ 8 IRT-4M 3rd mixed %**	**10 IRT-3M/ 10 IRT-4M 4th mixed %**	**8 IRT-3M/ 12 IRT-4M 5th mixed %**
CR-1	4.2	4.0	4.1	4.1	4.1	4.2
CR-2	4.2	3.8	3.8	3.8	3.8	4.0
CR-3	3.2	2.7	2.7	2.7	2.7	2.7
CR-4	3.2	3.0	2.7	2.7	2.7	2.7
AR	0.5	0.6	0.6	0.6	0.6	0.6
SR-1	1.9	1.9	1.9	1.9	2.0	1.8
SR-2	2.0	1.9	1.9	1.9	1.9	1.8
SR-3	1.2	1.3	1.3	1.3	1.3	1.3
All SR	5.6	5.7	5.7	5.6	5.6	5.2

	6 IRT-3M/ 14 IRT-4M 6th mixed %	**4 IRT-3M/ 16 IRT-4M 7th mixed %**	**2 IRT-3M/ 18 IRT-4M 8th mixed %**	**20 IRT-4M Full LEU %**
CR-1	4.3	4.5	4.4	4.3
CR-2	4.1	4.2	4.1	4.1
CR-3	2.7	2.8	2.8	2.9
CR-4	2.7	2.8	2.8	2.8
AR	0.6	0.6	0.7	0.6
SR-1	1.8	1.8	1.8	1.9
SR-2	1.7	1.8	1.8	1.9
SR-3	1.3	1.3	1.3	1.3
All SR	5.3	5.3	5.4	5.6

CR – Control (shim) rod, AR - Automatic Rod, SR – Safety Rod

Table 3, Reactivity Worth of Control/Safety Rods (%), (Uncertainty less than 2.0 %)

Steady-State Thermal Hydraulics Results

Steady-state thermal hydraulics analyses were performed using the PLTEMP code [6]. The fuel tubes are modeled as parallel plates and the coolant flows from the top to the bottom of the fuel. Detailed power density distributions were calculated using the MCNP4C code [5]; the fuel tubes are modeled as squares with sharp corners and the power densities are calculated for each of the flats of each fuel tube, and fifteen axial nodes are used.

Based on the specifications for the LEU/HEU fuel assemblies the maximum temperature in the clad surface must be less than 98 ºC for IRT-4M and less than 100 ºC for IRT-3M, and the Catalogue Description specifies a minimum ratio to onset of nucleate boiling (ONBR) equal to 1.3 using Bergles and Rohsenow correlation for IRT-4M and equal to 1.4 using the Forster Greif correlation for IRT-3M. The results of steady-state thermal-hydraulics calculations performed with the PLTEMP code for the HEU core, all mixed cores and the LEU core are presented in Table 4, . For calculations results presented in Table 4, and Table 5, the inlet water temperature is equal to 45 °C for active core of reactor and the total power of 10 MW for the HEU core (18 IRT-3M) and 11 MW for all other cores were used; the difference in the two tables is the meat power fraction: 0.94 in former and 0.90 in latter. The results in Table 4 show that the catalog limits on maximum clad temperature and minimum ONBR are satisfied for all core cycles during the transition from HEU to LEU fuel.

Core Configuration	**IRT-3M Fuel Assemblies**				**IRT-4M Fuel Assemblies**			
	ONBR	**Clad Max Temp, ºC**	**Peak Power Density (kW/cc)**	**FA Location**	**ONBR**	**Clad Max Temp, ºC**	**Peak Power Density (kW/cc)**	**Location**
18 IRT-3M	1.54	94.9	3.14 / 3.28	3-4 / 4-4	N/A			
16 IRT-3M/4 IRT-4M	1.44	99.4	3.5	3-5	1.59	87.1	2.05 / 1.59	5-5 / 4-4
14 IRT-3M/6 IRT-4M	1.47	98.1	3.41/2.61	3-5/3-3	1.64	85.5	1.94/1.53	4-4/5-4
12 IRT-3M/8 IRT-4M	1.52	96	3.25/2.55	3-5/3-3	1.59	86.9	2.02/1.6	4-4/4-4
10 IRT-3M/10 IRT-4M	1.57	94	3.11/2.47	3-5/3-3	1.36	94.5	2.13/1.92	3-4/4-4
8 IRT-3M/12 IRT-4M	1.67	90.6	2.84/2.40	3-3/3-3	1.41	92.6	2.02/1.98	3-4/5-5
6 IRT-3M/14 IRT-4M	1.71	89.3	2.76/2.34	3-3/3-3	1.44	91.3	1.95/1.94	3-4/4-4
4 IRT-3M/16 IRT-4M	1.99	82.4	2.26/2.03	5-2/4-2	1.56	87.4	2.02/1.92	4-4/3-3
2 IRT-3M/18IRT-4M	2.02	81.8	2.21/1.99	5-7/4-2	1.34	95.1	2.12/2.00	3-4/4-4
20 IRT-4M	N/A				1.36	94.5	2.10/2.08	3-4/4-4

Table 4, Steady-state thermal hydraulics calculations results, fraction of power deposited in fuel meat 0.94 used for the analysis.

Since in the Catalog for the IRT-3M FA the fraction of power deposited in the fuel meat is assumed to be equal to 0.90, the steady-state thermal hydraulics results are presented in Table 5, using those fractions.

	Core	**ONBR**	**Clad Maximal Temperature, °C**	**Peak Power Density, kW/cc**	**FA location**
Full HEU	18 IRT-3M	1.59	93.00	3.18/3.32	3-4/4-4
1st mixed	16 IRT-3M / 4 IRT-4M	1.49	97.30	3.55/3.39	3-5/3-3
2nd mixed	14 IRT-3M / 6 IRT-4M	1.49	97.10	3.54/3.38	3-5/3-3
3rd mixed	12 IRT-3M / 8 IRT-4M	1.49	96.80	3.50/3.33	3-5/3-3
4th mixed	10 IRT-3M / 10 IRT-4M	1.62	92.10	3.15/2.99	3-5/3-3
5th mixed	8 IRT-3M / 12 IRT-4M	1.73	88.90	2.88/2.87	3-3/3-3
6th mixed	6 IRT-3M / 14 IRT-4M	1.77	87.70	2.78/2.80	3-3/3-3
7th mixed	4 IRT-3M / 16 IRT-4M	2.06	81.00	2.29/2.22	5-2/4-2
8th mixed	2 IRT-3M / 18 IRT-4M	2.10	80.30	2.24/2.19	5-7/4-2

Table 5, Steady-state thermal hydraulics calculations results for fraction of power deposited in fuel meat 0.9 for IRT-3M.

Operating power limits were also defined for higher coolant inlet temperatures. The results of thermal hydraulics calculations using the PLTEMP code for inlet water temperature 48 °C, for all cores are presented in Table 6, . These results show the maximum operating power to meet the FA Catalogue Description.

Core	IRT-3M Temperature limit for IRT-3M - 100 °C			IRT-4M Temperature limit for IRT-4M - 98 °C			Factor	Power, MW
	Peak Heat Flux, MW/m^2	ONBR	Clad Surface Temperature, °C	Peak Heat Flux, MW/m^2	ONBR	Clad Surface Temperature, °C		
18 IRT-3M	0.908	1.50	97.1				1.0000	11.0
1st mixed	0.966	1.44	99.8	0.765	1.58	87.8	0.9630	10.7
2nd mixed	0.969	1.44	99.9	0.748	1.60	87.6	0.9910	10.9
3rd mixed	0.947	1.46	99.0	0.784	1.53	89.1	0.9790	10.8
4th mixed	0.890	1.53	96.2	0.863	1.32	96.9	1.0000	11.0
5th mixed	0.820	1.63	92.9	0.823	1.36	94.9	1.0000	11.0
6th mixed	0.797	1.67	91.6	0.792	1.40	93.6	1.0000	11.0
7th mixed	0.656	1.94	84.8	0.788	1.51	89.9	1.0000	11.0
8th mixed	0.646	1.97	84.1	0.864	1.30	97.4	1.0000	11.0
20 IRT-4M				0.858	1.32	96.7	1.0000	11.0

Table 6, Thermal hydraulics calculations results for inlet water temperature 48 °C.

Kinetics Parameters and Reactivity Coefficients

The kinetics parameters and reactivity coefficients are important for the determination of the core response after an incident/transient. Table 7, presents the results for full HEU, 1st mixed and full LEU cores. The results show, that the reactivity coefficients and the kinetics parameters for the first mixed and full LEU core are similar to those for the reference IRT-3M HEU core.

	HEU core 18IRT-3M	**1st mixed core 16 IRT-3M, 4IRT-4M**	**Full LEU core 20 IRT-4M**
Coolant Temperature Reactivity Coefficient (%/°K)			
293 to 400 K	-9.2E-3	-9.5E-3	-9.1E-03
400 to 600 K	-7.1E-3	-7.7E-3	-7.3E-03
293 to 600 K	-7.9E-3	-8.3E-3	-7.9E-03
Coolant Void Reactivity Coefficient (%/% void)			
0 to 5%	-2.8E-1	-2.6E-1	-2.7E-01
5 to 10%	-3.0E-1	-2.9E-1	-2.9E-01
0 to 10%	-2.9E-1	-2.8E-1	-2.8E-01
Doppler Reactivity Coefficient (%/°K)			
293 to 400 K	-2.2E-3	-2.1E-3	-2.3E-03
400 to 600 K	-1.5E-3	-1.7E-3	-2.2E-03
293 to 600 K	-1.7E-3	-1.8E-3	-2.2E-03
Effective Delayed Neutron Fraction, β_{eff} [6]			
	7.6E-3	7.6E-3	7.6E-3
Prompt Neutron Generation Time, µs			
	52	53	56

Table 7, Kinetics parameters and reactivity coefficients (uncertainty less than 3 % for all parameters)

Conclusions

- Detailed power densities and the neutronics kinetics parameters (reactivity feedbacks, generation time and delayed neutron fractions) have been calculated for conversion of WWR-SM from HEU to LEU.
- Shutdown margin is satisfied for all cores.
- Control rod worths and reactivity feedback coefficients have small variation among cores.
- Clad temperature and ONBR limits are satisfied for all cores.

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