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Some Main Results of Commissioning of The Dalat Research Reactor with Low Enriched Fuel

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Abstract: After completion of design calculation of the Dalat Nuclear Research Reactor (DNRR) for conversion from high-enriched uranium fuel (HEU) to low-enriched uranium (LEU) fuel, the commissioning programme for DNRR with entire core loaded with LEU fuel was successfully carried out from 24 November 2011 to 13 January 2012. The experimental results obtained during the implementation of commissioning programme showed a good agreement with design calculations and affirmed that the DNRR with LEU core have met all safety and exploiting requirements.

Keywords: *HEU, LEU, physics start up, energy start up, effective worth, Xenon poisoning, Iodine pit.*

I. INTRODUCTION

Physics and energy start-up of the Dalat Nuclear Research Reactor (DNRR) for full core conversion to low enriched uranium (LEU) fuel were performed from November 24th, 2011 until January 13th, 2012 according to an approved program by Vietnam Atomic Energy Institute (VINATOM). The program provides specific instructions for manipulating fuel assemblies (FAs) loading in the reactor core and denotes about procedures for carrying out measurements and experiments during physics and energy start-up stages to guarantee that loaded LEU FAs in the reactor core are in accordance with calculated loading diagram and implementation necessary measurements to ensure for safety operation of DNRR.

Main content of the report is a brief presentation of performed works and achieved results in the physics and energy start up stages for DNRR using LEU fuel assemblies, that is from starting loading LEU fuel to the reactor core (November, 24th, 2011) until finishing 72 hours testing operation without loading at nominal power (December, 13rd, 2011).

II. PHYSICS START UP

Physics startup of reactor is the first phase of carrying out experiments to confirm the accuracy of design calculated results, important physical parameters of the reactor core to meet safety requirements. Physics startup includes fuel loading gradually until to approach criticality, loading for working core and implementing experiments to measure parameters of the core at low power such as control rods worth, shutdown margin, temperature effect,…

A. Fuel loading to approach criticality

The loading of LEU FAs to the reactor core was started on November, 24th, 2011 following a predetermined order in which each step loaded one or group LEU FAs to the reactor core. After each step, the ratio of

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$\frac{N_0}{N_i}$ (N_0 is initial number of neutron count rate, N_i is that to be obtained after step *ith*) was evaluated to estimate critical mass. At 15h35 on November, 30th, 2011 the reactor reached critical status with core configuration including 72 LEU FAs and neutron trap in center (see **Fig. 1** and **2**).

Established critical core configuration with 72 LEU FAs having neutron trap is in good agreement with design calculated results. With 72 LEU FAs, by changing position of some fuel assemblies, all new criticality conditions were achieved with lesser inserting position of regulating rod. It is concluded that the above critical configuration (**Fig. 1**) is the minimum one among established configurations. The critical mass of Uranium is 15964.12 g in which Uranium-235 is 3156.04 g.

B. Fuel loading for the working core

After completion of fuel loading to approach criticality, fuel loading for working core was carried out from December, 6th, 2011 to December, 14th, 2011. During fuel loading for working core, effective worth of loaded fuel assemblies and shutdown margin were preliminarily evaluated to ensure shutdown margin limit not be violated. **Fig. 3** shows the current working core of DNRR, including 92 LEU FAs (80 fresh LEU FAs and 12 partial burnt LEU FAs, the burn up about 1.5 to 3.5 %) and neutron trap at the center. Total mass of U-235 that was loaded to the reactor core is about 4246.26 g. Shutdown margin (or subcriticality when 2 safety rods are fully withdrawn) is 2.5 $ (about 2% Δk/k), smaller than calculated value (3.65 $) but still completely satisfy the requirement >1% for the DNRR. Excess reactivity of the core configuration is about 9.5 $, higher than calculated value (8.29 $), ensuring operation time of the reactor more than 10 years with recent exploiting condition. So, it can be said that the current working core meets not only safety requirements but reactor utilization also (ensure about shutdown margin and sufficient excess reactivity for reactor operation and utilization).

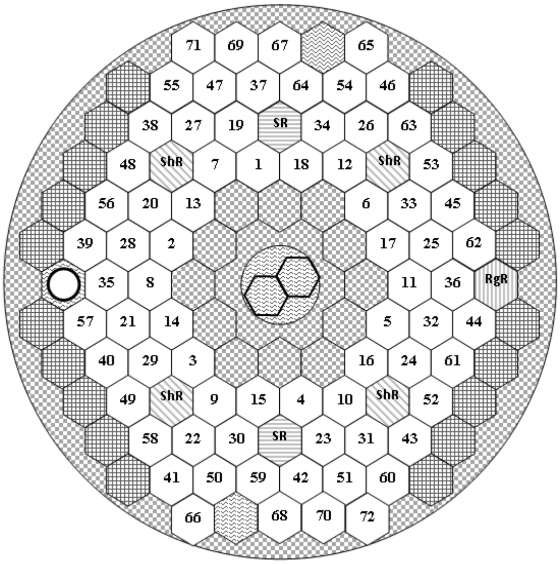

Fig. 1. Critical core configuration and order of loaded fuel assemblies

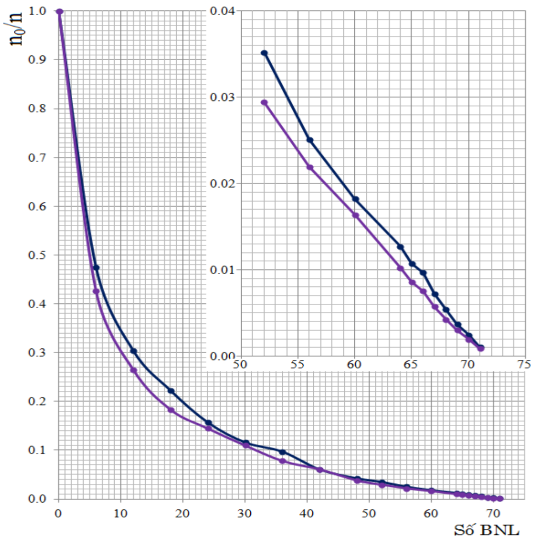

Fig. 2. N_0/N_i ratio versus number of FAs loading to the core

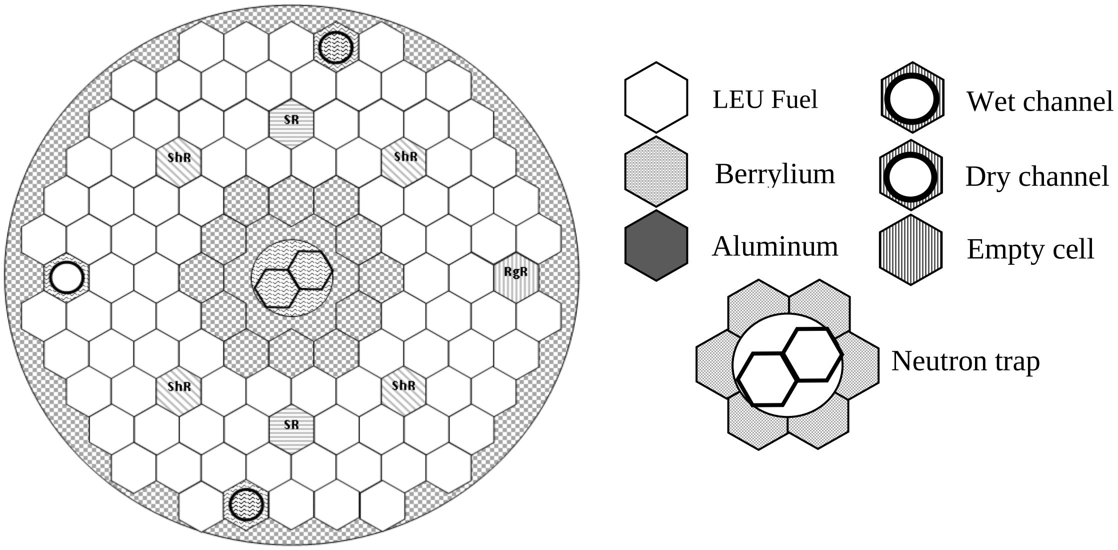

Fig. 3. Working core configuratiom with 92 LEU FAs

C. Performed experiments in the working core configuration

Determination of control rod worth

To calibrate control rod worth, doubling time method was applied for regulating rod while reactivity compensation method was used for shim rods and safety rods. The calibration of control rods of DNRR were implemented two time during fuel loading for working core in configuration with 82 fresh LEU FAs and 92 LEU FAs.

Control rods worths and integral characteristics in core configuration with 92 LEU FAs are presented in **Table I, Fig. 4** and **5**. Measured results were smaller than design calculated results about 12% in average.

Table I. Effective worth of regulating rod, 4 shim rods and 2 safety rods in core configuration with 92 LEU FAs.

Control Rod	Effective reactivity ($)	
	Measured value	Calculated value
Regulating rod	0.495	0.545
Shim rod 1	2.966	3.237
Shim rod 2	3.219	3.263
Shim rod 3	2.817	3.473
Shim rod 4	2.531	3.086
Safety rod 1	2.487	2.744

Safety rod 2	2.195	2.795

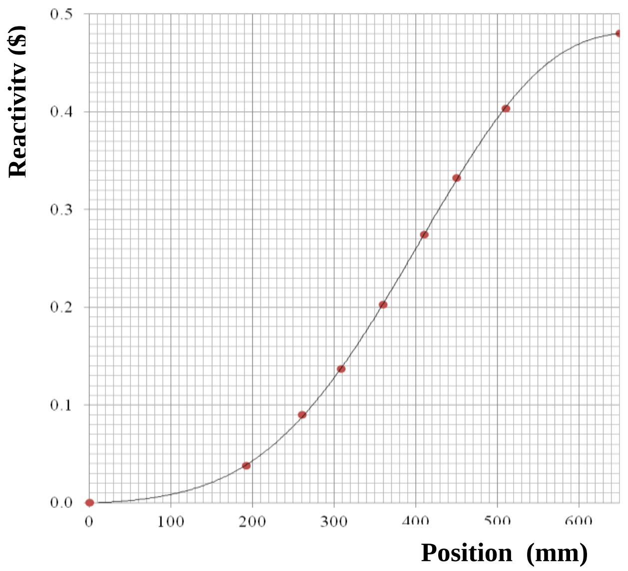

Fig. 4. Integral characteristics of regulating rod

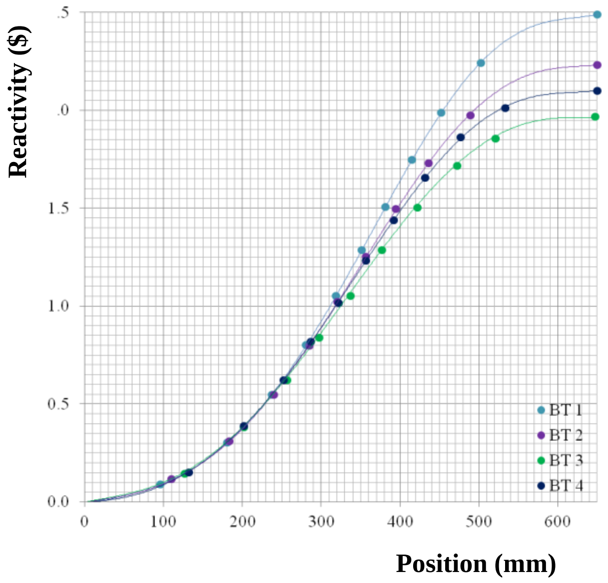

Fig. 5. Integral characteristics of 4 shim rods

Thermal neutron flux distribution measurement in the reactor core

Measurement of thermal neutron flux distribution following axial and radial in the reactor core was carried out by Lu metal foils neutron activation. A number of positions in the reactor core were chosen to measure thermal neutron flux distribution including neutron trap, irradiation channels 1-4 and 13-2, and 10 FAs at the cells: 1-1, 2-2, 2-3, 2-7, 3-3, 3-4, 4-5, 6-4, 12-2 and 12-7. **Figs 6** to **9** present the measured results of axial and radial neutron flux distributions of the reactor core.

From the measured results, it can be seen that the maximum peaking factor of 1.49 is achieved at outer corner of hexagonal tube of the fuel assembly in cell 6-4. Neutron distribution of working core has large deviation from North (thermal column) to South (thermalizing column). Neutron flux in southern region of the core (cell 12-1 and 12-7) is about 28 % smaller than those in Northern region (cell 2-1 and 2-7). The asymmetry of the reactor core has reason from the not identical reflector that was noted from the former HEU fuel core.

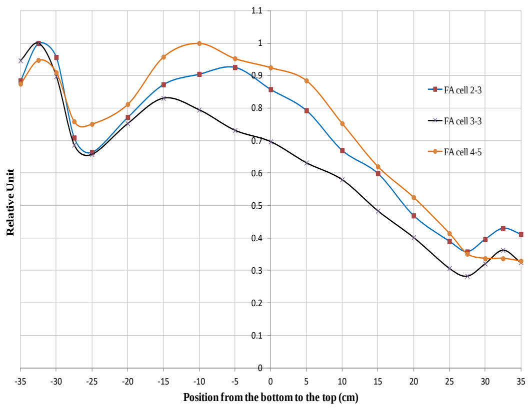

Fig. 6. Axial thermal neutron flux distribution in the fuel assemblies

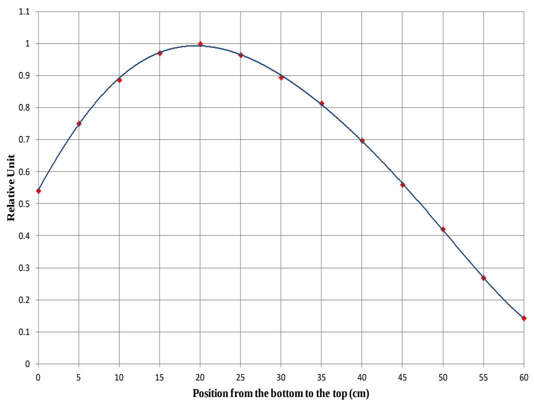

Fig. 7. Axial thermal neutron flux distribution in the neutron trap

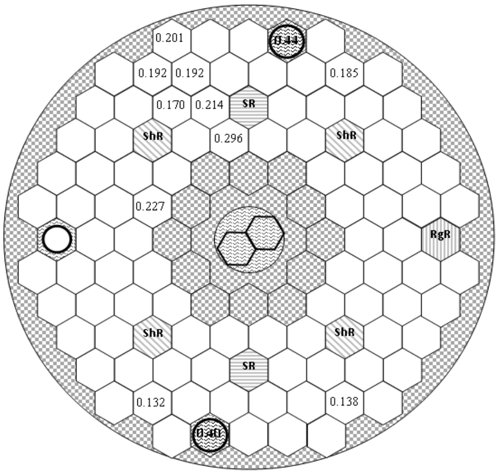

Fig. 8. Thermal neutron flux distribution of FAs and irradiation positions in comparison with neutron trap.

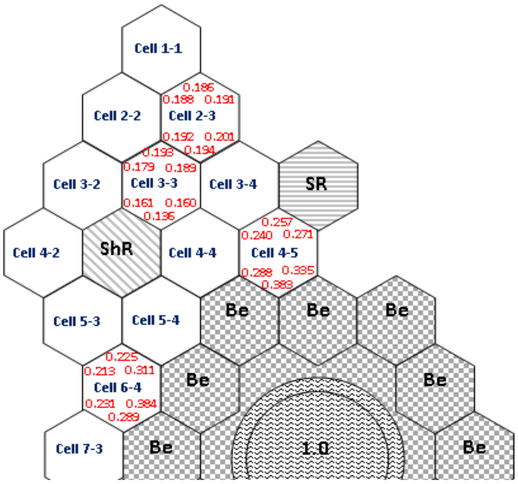

Fig. 9. Thermal neutron flux distribution of the FA's corners in comparison with neutron trap

Determination of effective worth of FAs, beryllium rods and void effect

The measurements of effective worth of FAs, beryllium rods and void effect (by inserting an empty aluminum tube with diameter of 30 mm) were also performed. These are important parameters related to safety of the reactor. Positions for measurement of effective reactivity of FAs, Be rods and void effect were chosen to examine the distribution, symmetry of the core and the interference effects at some special positions. Effective reactivity of FAs, beryllium rods and void effect were determined by comparing position change of control rods before and after withdrawing FA or beryllium rod or before and after inserting watertight aluminum tube. Reactivity worth values were obtained using integral characteristics curves of control rods.

Figs 10÷12 show the measured results of effective worth of 14 FAs in the reactor core at different positions; effective worth of beryllium rods around neutron trap and a new beryllium rod at irradiation channel 1-4; void effect at neutron trap, irradiation channel 1-4 and cell 6-3, which surrounded by other FAs.

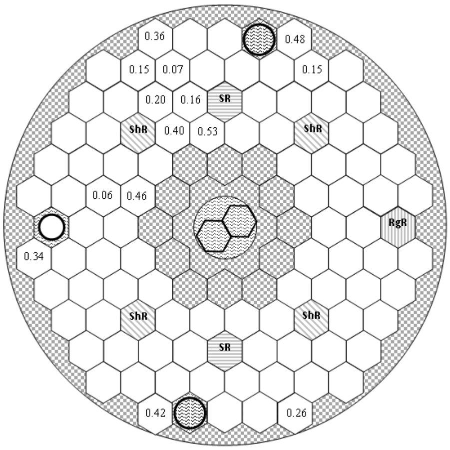

Fig. 10. Effective worth of FAs in the reactor core

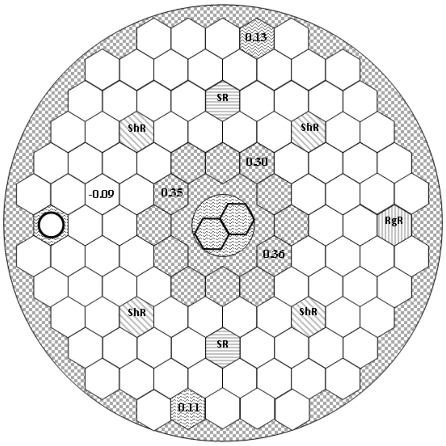

Fig. 11. Effective worth of Be rods in the reactor core

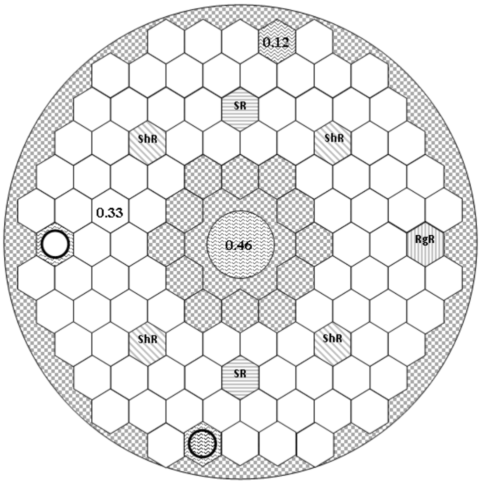

Fig. 12. Measured results of void effect at some positions in the reactor core

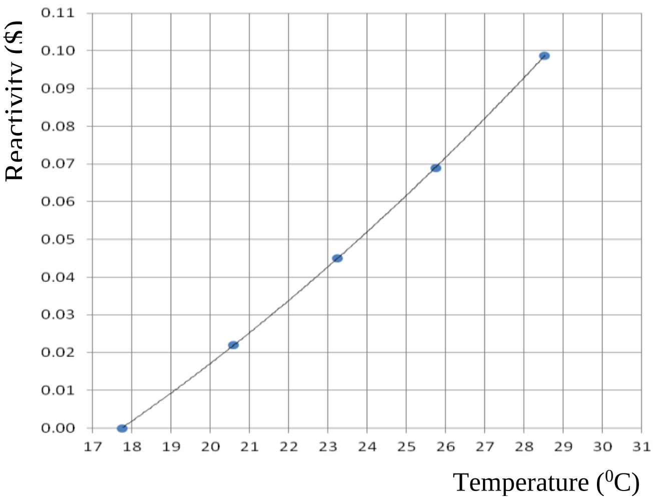

Fig. 13. Negative reactivity insertion dependent on pool water temperature

The most effective worth of fuel assembly measured at cell 4-5 is 0.53 $. Measured results of effective reactivity of fuel assemblies and Be rods show a quite large tilting of reactor power from North to South direction. Void effect has negative value in the reactor core (cell 1-4 and 6-3) while positive in the neutron trap. Void effect in neutron trap has positive value because almost neutrons coming in neutron trap are thermalized, that is absorption effect of water in neutron trap is dominant compared to moderation effect. The replacement of water by air or decreasing of water density when increasing steadily of temperature introduces a positive reactivity. With the core using HEU fuel also has positive reactivity of void in neutron trap.

Determination of temperature coefficient of moderator

Temperature coefficient of moderator is the most important parameter, demonstrating inherent safety of reactor. To carry out experiment, the temperature inside reactor pool was raised about 10^{0}C by operating primary cooling pump without secondary cooling pump. To measure temperature coefficient of moderator, criticality of the reactor was established after each increased step of pool water temperature about 2.5^{0}C. Basing on the change of regulating rod position (due to change of temperature in the reactor core) the temperature coefficient of moderator was determined.

Heating process of water in reactor pool by operating primary cooling pump took long time so water in neutron trap also heated up and inserted positive reactivity (as explanation in measurement of void effect), as opposed to temperature effect in the reactor core. So, a hollow stainless steel tube 60 mm diameter was inserted in neutron trap to eliminate positive temperature effect of neutron trap.

Fig. 13 shows measured results of temperature coefficient of moderator with initial temperature of 17.7 ^{o}C. Based on these results, the temperature coefficient of moderator is determined about -9.1×10^{-3} $/^{o}C. Measured result without steel pipe containing air at neutron trap was about -5.2×10^{-3} $/^{o}C. Thus, temperature coefficient of moderator including neutron trap still has negative value. Temperature coefficient of moderator of the core loaded with 88 HEU FAs measured in 1984 was -8.0×10^{-3} $/^{o}C.

III. ENERGY START-UP

A. Power ascension test

On January 6th, 2012 reactor power has been increased at levels of 0.5% nominal power, 10% nominal power and 20% nominal power. At each power level, thermal neutron flux in neutron trap, irradiation channels 1-4, 13-2 and rotary specimen was measured by using Au foil activation method. Also, on January 17th, 2012 thermal neutron flux of positions mentioned above was measured at power level 100%. Measured results of thermal neutron flux at several irradiation positions in the reactor core with different power levels are presented in **Table II**.

Table II. Measured results of thermal neutron flux at several irradiation positions at different reactor power levels

Irradiation positions	**Power (% Nominal power)**			
	0,5	**10**	**20**	**100**
Neutron trap	1.143E+11	2.063E+12	4.174E+12	2.122E+13
Channel 1-4	5.288E+10	9.719E+11	1.965E+12	8.967E+12
Channel 13-2	4.749E+10	8.542E+11	1.682E+12	N/A
Rotary Specimen	N/A	N/A	N/A	4.225E+12

Based on the reactor power determined by thermal neutron flux measurements at low power levels, on January 9th, 2012 the reactor was ascended power: 0.5%, 20%, 50%, 80% and then operated at 80% nominal power during 5 hours for determination of thermal power and examination of technological parameters and gamma dose before raising the reactor power to nominal level.

Thermal power of the reactor corresponding to 80% nominal power level (based on indication of control system) after 5 hours calculated based on primary cooling system parameters was about 372 kW. This value enables us to raise the reactor power to full power level. 15h32 on January, 9th, 2012 the reactor was raised to 100% nominal power and maintained at this power about 65 hours before decreasing to 0.5% nominal power to measure Xenon poisoning transient. **Table III** presents the values of thermal power of the reactor during the first 8 hours after the reactor reached 100% nominal power. The data indicate that thermal power is just only about 460 kW, lower than design nominal power about 10%.

Table III. Thermal power of the reactor with operation time after the reactor reached 100% nominal power

Time	**T_{in} (1) [°C]**	**T_{out} (1) [°C]**	**G_I [m^3/h]**	**P_I [kW]**
15h30	29,2	22,4	49,4	390
16h00	30,3	22,9	49,3	423
17h00	31,0	23,1	49,8	456
18h00	31,0	23,0	49,8	462
1h00	30,9	22,9	49,8	462
20h00	30,8	22,9	49,6	454
21h00	30,8	22,9	49,8	456
22h00	30,7	22,8	50,5	457
23h00	30,6	22,7	50,1	459
24h00	30,5	22,6	49,6	455

B. Xenon poisoning transient and Iodine hole

The experiment to determine the curve built up of Xenon poisoning and then calculating its equilibrium poisoning was conducted from January 9th, 2012 to January 12th, 2012 when the reactor was in 100% nominal power (indicating of control system without adjusting power) . Next, Iodine hole was also determined from 12 to January 13th, 2012 after reducing power of the reactor from 100% to 0.5% nominal power by monitoring the shift position of regulating rod.

Fig. 14 presents measured results of Xenon poisoning curve and Iodine pit of the above experiment. Xenon equilibrium poisoning and other effects is totally about -1.1 β_{eff} and the maximum depth of Iodine pit determined about -0.15 β_{eff} after 3.5 hours since the reactor was down to 0.5% nominal power. After adjusting thermal power up to 500 kW, during the long operation from March, 12-16, 2012, after the reactor was operated 68 hours at nominal power, total value of poisoning and temperature effects is about -1.32 β_{eff}.

C. Power adjustment

In the process of gradually raising power in energy start-up, although power indication on control system was 100% but calculated thermal power of the reactor through flow rate of primary cooling system and difference between inlet and outlet temperatures of the heat exchanger was only 460 kW, smaller than nominal power about 10%. The reason was mainly due to power density of the core using 92 LEU FAs were higher than the mixed core using 104 FAs before. The adjustment to increase thermal power of the reactor was performed by changing the coefficients on the control panel. After adjusting, the reactor was operated to determine thermal power at power setting 100%. The results of thermal power obtained from the next long operation was about 510.5 kW. This value includes 500 kW thermal power of the reactor and about 10 kW generated by primary cooling pump.

D. Measurement of neutron flux and neutron spectrum after power adjustment

After carrying out reactor power

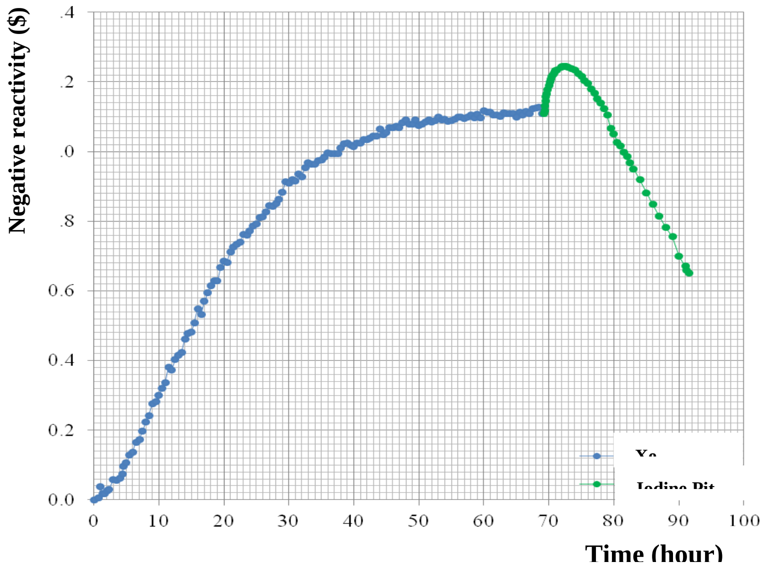

Fig. 14. Negative reactivity insertion by Xenon poisoning with operation time and Iodine

adjustment, thermal neutron flux at some irradiation positions in the reactor core and neutron spectrum in neutron trap were measured again by neutron activation foils. Measured maximum neutron flux at neutron trap was 2.23 × 10^{13} n/cm^2.s (compared with calculated result was 2.14÷2.22 × 10^{13} n/cm^2, depending on shim rods position). Those in channel 1-4 and 13-2 were 1.07 × 10^{13} n/cm^2.s and 8.61×10^{12} n/cm^2.s, respectively. The experimental error of neutron flux was estimated about 7%.

From reaction rate measured by foils irradiation method in neutron trap, neutron spectrum obtained by SAND-BP computer code. Obtained results of neutron spectrum in neutron trap (**Fig. 15**) showed that comparing with mixed-core HEU-LEU fuel, when neutron trap having thinner Beryllium layer, thermal neutron flux increased while epi-thermal and fast neutron flux decreased with a significant percentage.

IV. CONCLUSIONS

After completing design calculation and preparation, start up of DNRR with entire LEU FAs core was implemented following a detailed plan. As a result, physics and energy start up were carried out successfully. DNRR was reached criticality at 15:35 on November, 30th, 2011 with 72 LEU FAs, consistent with calculated results. Then, the working core with 92 LEU FAs has been operating 72 hours for testing at nominal power during from January, 9th, 2012 to January, 13th, 2012.

Experimental results of physical and thermal hydraulics parameters of the reactor during start up stages and long operation cycles at nominal power showed very good agreement with calculated results. On the other hand, experimental results of parameters related to safety such as peaking factor, axial and radial neutron flux distribution of reactor core, negative temperature coefficient, temperature of the reactor tank, temperature at inlet/outlet of primary cooling system and secondary cooling system,…it could be confirmed that current core configuration with 92 LEU FAs meets the safety and exploiting requirements.

Measured neutron flux at irradiation positions and actual utilization of the reactor after full core conversion also showed that the reactor core using LEU fuel is not much different than previous core using HEU fuel.

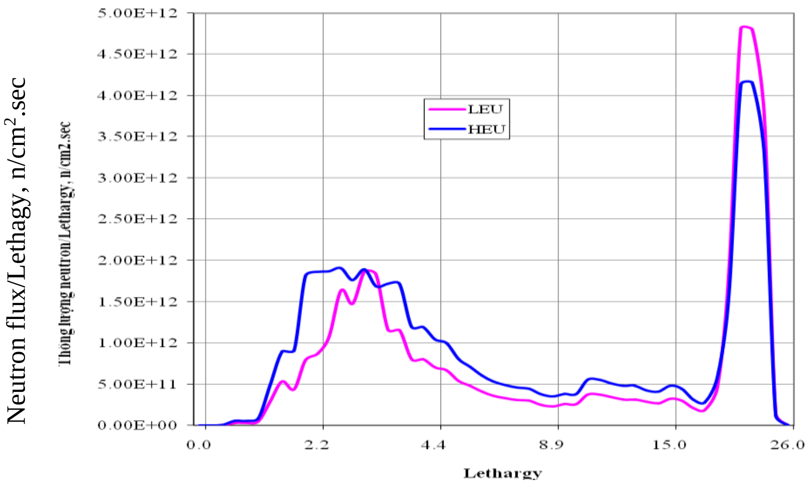

Fig. 15. Measured neutron spectrum in neutron trap before and after conversion

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