Study of Neutronic and Temperature Distribution During Enrichment Reduction for BN-350 Reactor

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Abstract

This paper represents the neutronic and thermal-hydraulic calculations for the conversion of BN-350 from 27% to 7% enriched Uranium fuel elements. Mixed enrichment cores has been studied where low enrichment uranium (LEU) cores fresh fuel elements substitute gradually the high enrichment uranium (HEU) depleted fuel elements in the equilibrium core.

Thermal hydraulic calculations have been carried out to determine changes in the characteristics of the converted reactor during steady state conditions and transient response to a coolant flow loss.

1- Introduction

Several studies for the conversion of BN-350 loop type reactor have been studied. So they concluded that[1-3], in order to match the cycle length of the current 27% high enriched uranium fuel design HEU with 20% enriched fuel LEU(low enriched uranium), an uranium density of about 11gm/cm^3 is required.

The BN-350 reactor will be converted to use the 7% enriched uranium LEU fuel elements which have only minor changes of the fuel plates and no change in the design of the fuel element geometry. With the same element geometry, the thermal hydraulic characteristics of the core should be almost identical with both HEU and LEU fuels. Neutronic calculations have been performed using well verified computer codes, DAIXY code[4], [5], and another program established (JAM1) using a personal computer.

A thermal hydraulic program (JAM2) [6] has been developed to analyze the behavior of the reactor in steady conditions at nominal pond during primary pumps failure. Table (1) gives some important physical properties of the BN-350 reactor [3] [7]-[10]:

Table (1): Reactor and fuel element design descriptions with the HEU and LEU fuels

Property	HEU	LEU
Reactor type	Loop type	Loop type
Steady –state power level, Mw	1000	1000
U^{235} density in fuel element:		
External plate, g/cm^3	8	8.11
Internal plate, g/cm^3	9.5	9.523
Uranium enrichment, %	27	7
Number of reference core configuration	211	211
Control blade material	B_4C	B_4C
Number of control blades	12	12
Number of fuel assemblies	120	109
Coolant	Na	Na
Reflector	Depleted UO_2	Depleted UO_2
Fuel mass(tHM) (tonnes of heavy metals)	1.170 ^{235}U	1.3851 ^{235}U
Lattice pitch, mm	98	98
Primary coolant velocity, m/s	8	8
Inlet temperature, C^0	300	300
Outlet temperature, C^0	500	500
fuel rod thickness, mm	6.1	6.1
fuel rod height, mm	1060	1182
Active length, mm	1060	1060
Clad thickness SS316, mm	0.35	0.35
Coolant flow area, cm^2	5450	5450
Fuel element composition	UO_2PuO_2	UO_2PuO_2

2-Neutronic calculations

Cross sections were prepared for different regions in the core using the reactor physics constantsANL-5800[11], [12], reactor physics constants. Different cell models were needed to generate appropriate cross sections for the various reactor regions in the standard four group structure. Most of the results of this study are based on two dimension multigroup diffusion calculations using DAIXY code and JAM1 personal program, with buckling are imposed for the axial dimension [13]**.**

Fig.(1), shows the core arrangement of BN-350 reactor consisting of three regions of 898 fuel elements with depleted UO_2 reflected, the experimental value of effective multiplication factor K_{eff} [5] estimated for the reference HEU core using UO_2PuO2 was 1.0288065.

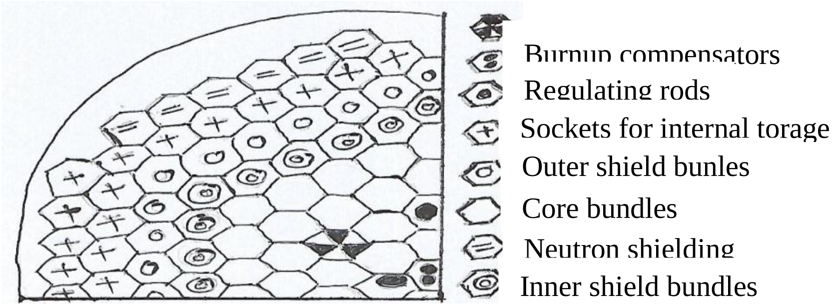

Fig.(1) BN – 350 zones with assembly arrangements.

The DAIXY and JAM1 were used to calculate the K_{eff} for both HEU and LEU reference core with 898 fuel elements using the same axial buckling [3]. The K_{eff} results are shown in table(2) for LEU and HEU cases, in which the code predicts well the K_{eff} experimentally determined.

Table (2): Effective multiplication factor calculated for BN-350 with HEU and LEU fuels.

Case	Daixy		JAM1		References*	
	K_{eff}	%Δk/k	K_{eff}	%Δk/k	K_{eff}	%Δk/k
HEU	1.0321169	2.883400	1.0329612	2.0806	1.028806	2.8
LEU	1.0301165	0.117022	1.0309513	0.9040	1.010101	0.9

*References:[3][5][7][11].

The reactor kinetics parameters have been calculated for the reference core at the end of equilibrium cycle for both HEU and LEU fuels [3][14][15]. By using the two dimensional diffusion theory perturbation capability of JAM1, the values of neutron generation time (ʌ), the prompt neutron lifetime (ℓ) and the effective delayed neutron fraction (βeff) were obtained and listed in table 3.

Table (3): Kinetics parameters for the HEU and LEU cores.

Core	Fuel type	ʌ (μs)	ℓ (μs)	β_{eff}
Reference	HEU	42.0	43.2098	0.0158
	LEU	39.0	39.3939	0.0146
Calculated	HEU	43.5	43.7618	0.0149
	LEU	40.3	40.3472	0.0141

The isothermal temperature and void coefficients of reactivity were computed separately as functions of temperature with noting the following effects:

1- Hardening of the neutron spectrum caused by increasing the temperature of the coolant only.

2 - Increasing in neutron leakage when the coolant density is decreased.

3 - Increasing in U-238 epithermal resonances absorption due to the increasing of the fuel element temperature (Doppler effect) [16].

The global temperature coefficient of reactivity is expressed in terms of $-\Delta\rho/\Delta T*10^{-3}$ /C^0 and obtain for the reference fresh fuel core with 1.761 for HEU fuel and 1.532 for the LEU fuel. The control worth calculations for the control blades (12 fully inserted B_4C-SS316) and the fuels of both HEU and LEU, compared with the reference and equilibrium cases, are based on a diffusion calculation. Cross sections were used from ANL-5800 and from [11][12][17]. The reactivity ρ corresponding to the control blades using DAIXY code, are shown in table (4) for both reference and equilibrium cores using HEU and LEU fuels.

Table (4): Control worth of the B_4C control blades for HEU and LEU cores

core	Fuel type	K_{out} *	K_{in} **	Control worth
Reference	HEU	1.0288065	0.9153320	0.1134745
	LEU	1.0309132	0.8631890	0.1677242
Calculated	HEU	1.0321169	0.9831417	0.0489752
	LEU	1.0302966	0.9528554	0.0998154

* K_{out}: K_{eff} when control rods up.

** K_{in}: K_{eff} when control rods down.

Mixed enrichment cores might be considered as an option for the conversion of the BN-350 reactor where LEU fresh elements substitute gradually the HEU fuel in the equilibrium core. This situation is expected to occur during the core conversion and in the planning of such conversion it has to predict the accurate behavior of the mixed cores.

For the mixed core calculations it will be used the same shuffling pattern that was utilized for the equilibrium core.

3-Thermal – hydraulic calculations

The conversion of the BN-350 reactor from HEU fuel to LEU fuels was considered without changing the geometry of fuel element. The minor modifications in fuel plates were made in which the width of the fuel rod was changed from its actual values of 6.1mm to 7.256 mm in the LEU case. Thus, the thermal-hydraulic behavior of the converted core would be virtually identical to the HEU core [18].

The thermal-hydraulic calculations have been carried out using a thermal-hydraulic subroutine program JAM2 in order to determine changes in the characteristic of the converted reactor during steady conditions and transient response to a loss of coolant flow (LOCA) for both HEU and LEU reference core. However, the calculations for both types of the reference core fuels, HEU and LEU, confirm that there are minor changes in the thermal-hydraulic behavior, see table (1), and for this reason it will only be shown the results for the fresh LEU reference core.

For steady state case, the results of temperature distribution at the surface of fuel rod and the center were $670C^0$ and $369C^0$ respectively as shown in fig(2), which is indicates that temperature was fixed after about 10 seconds.

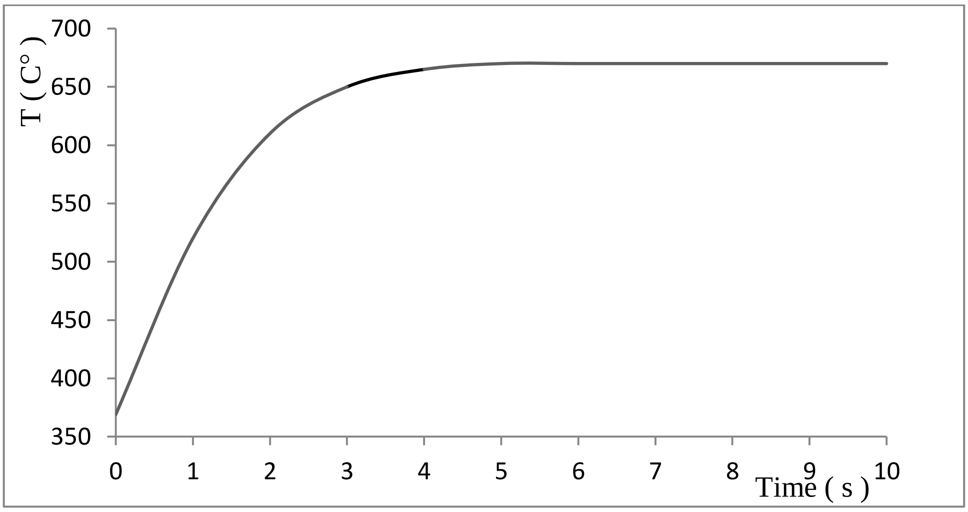

Fig. (2): Temperature distribution with time for fuel rods. (Steady state).

But for transient case, we show that after 151s the fuel fused because it reaches melting point, and the clad fused after 62s for the same reason, as shown graphically in fig.(3).

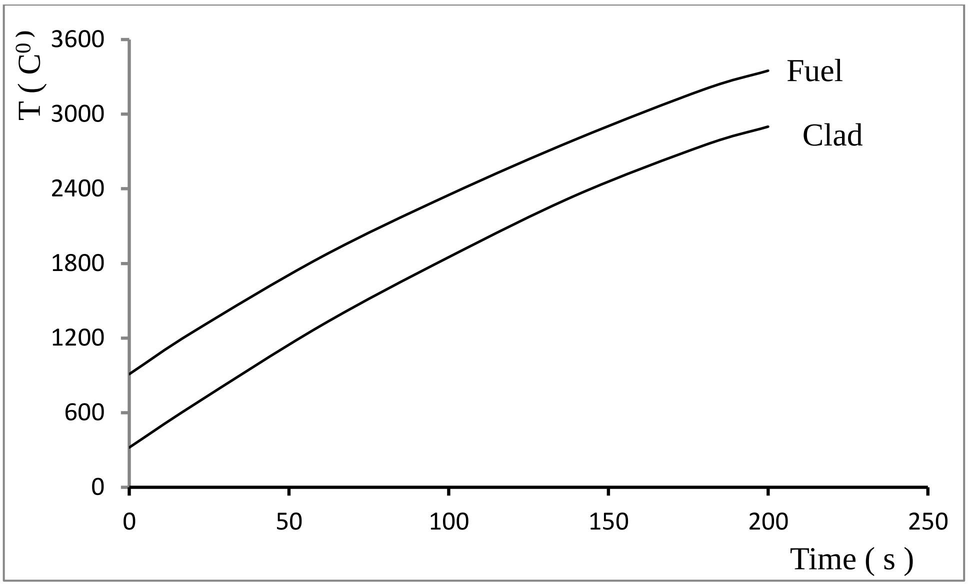

Fig. (3): Transient Temperature distribution in fuel rods (Fuel and Clad).

4-Conclusions

In every aspect, the BN-350 reactor can be converted to use 7% enriched uranium without modification in the design of the fuel element geometry where the fuel density changed from its actual values of 9.5gm/cm^3 to 9.523 gm/cm^3.

The most important neutronic effect in the equilibrium core performance as a result of the conversion, from 27% to 7% enriched uranium fuel, is the increasing of thermal flux from 10.1653x10^{15}n/cm^2.s, to 10.43668x10^{15}n/cm^2.s in the irradiation positions, and from 7.721287x10^{15}n/cm^2.s, to 8.156372x10^{15}n/cm^2.s for control rods.

Mixed enrichment cores might be considered as an option for the conversion of the reactor where LEU fuel elements substitute gradually the HEU fuels in the equilibrium core.

The thermal-hydraulic behavior for the reference core was identical to both HEU and LEU fuels. The effects of flow transient over the thermal-hydraulic characteristics of the reactor for the LEU reference core at beginning of life have demonstrated that it can operate at 1000Mwt.

For the equilibrium core, the flow through the fuel element channels has a reduction estimated in 10% in a relation with the reference core; consequently, the maximal heat flux is reduced for about 60% comparing the same configurations. It could be, thus, deduced that the reactor using equilibrium core is safer than the reference cores configuration, however, this conclusion must be confirmed.

CONFLICT OF INTERESTS
There are no conflicts of interest.

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دراسة التوزيع النيوتروني والحراري خلال تنقيص تخصيب المفاعلBN-350

الخلاصـــة

يمثل هذا البحث الحسابات النيوترونية والهيدروليكية لتحويل المفاعل BN – 350 من تخصيب عالي 27% الى تخصيب واطيء 7%. تمت دراسة قلبين ممزوجين بتخصيبين مختلفين حيث تم استبدال اقلام الوقود الخالصة من تخصيب اليورانيوم الواطيء LEW بتخصيب وقود يورانيوم عالي HEU من اقلام الوقود المنضب في حالة توازن القلب. طبقت الحسابات الحرارية الهيدروليكية لحساب تغيرات خصائص المفاعل المتحول خلال الحالة المستقرة والاستجابة العابرة لفقدان جريان المبرد.

الكلمات الدالة: BN-350، تخصيب، قلم وقود، عمل المضاعفة k_{eff}، زمن عمر النيوترون.