SOME QUESTIONS ON NUCLEAR SAFETY OF HEAVY-WATER POWER REACTOR OPERATING IN SELF-SUFFICIENT THORIUM CYCLE

by

Boris R. BERGELSON[1], Alexander S. GERASIMOV[1], and Georgy V. TIKHOMIROV[2]

Received on August 13, 2008; accepted in revised form in October 24, 2008

In this paper the comparative calculations of the void coefficient have been made for different types of channel reactors for the coolant density interval 0.8-0.01 g/cm^3. These results demonstrate the following. In heavy-water channel reactors, the replacement of D_2O coolant by H_2O, ensuring significant economic advantage, leads to the essential reducing of nuclear safety of an installation. The comparison of different reactors by the void coefficient demonstrates that at the dehydration of channels the reactivity increase is minimal for HWPR(Th), operating in the self-sufficient mode. The reduction of coolant density in channels in most cases is accompanied by the increase of power and temperatures of fuel assemblies. The calculations show that the reduction of reactivity due to Doppler effect can compensate the effect of dehydration of a channel. However, the result depends on the time dependency of heat-hydraulic processes, occurring in reactor channels in the specific accident. The result obtained in the paper confirms that nuclear safety of HWPR(Th) lies on the same level as nuclear safety of CANDU type reactors approved in practice.

Key words: thorium fuel cycle, CANDU reactor, nuclear safety

INTRODUCTION

The results of calculation studies presented in [1, 2] have substantiated feasibility of the self-sufficient mode of operation of a heavy-water power reactor in Th-U fuel cycle. This mode is based on standard technologies approved in practice during hundreds of reactor-years of exploitation of Canadian heavy-water reactors.

The experience of reliable exploitation of CANDU reactors with uranium fuel does not exclude the need of considering nuclear safety for this type of reactors with Th-U fuel. In the first place, this is connected with the fact that the fraction of delayed neutrons for ^{233}U fission $\beta_{\rm eff}$ = 0.00266. This is 2.6 times less than in fission of ^{235}U, for which $\beta_{\rm eff}$ = = 0.00682 [3]. Besides, the cross-section of absorption of thermal neutrons in ^{232}Th is about 2.7 times higher than in ^{238}U, while the cross-section of fission and the average yield of neutrons in one act of fission for ^{233}U and ^{235}U differ less than 10% [3]. For this reason, the transition to Th-U fuel in a thermal-neutron reactor requires the increase of ^{233}U content in ^{232}Th (in contrast with the ^{235}U content in ^{238}U) and, as a result, the possible increase of "'weight" of certain fuel assemblies and channels. The rate of transuranium element formation, which mainly determine the radiation danger of waste, is much higher in a reactor with uranium fuel than in a reactor with Th-U fuel.

In this paper, the results of calculation studies of nuclear safety problems for a heavy-water power reactor with Th-U fuel operating in the self-sufficient mode are presented. Throughout the paper, this reactor will be referred to as HWPR(Th). The code MCNP-5 based on Monte-Carlo method and the data library ENDF-B6.8 were used for the calculation of the reac-

Nuclear Technology & Radiation Protection
Scientific paper
UDC: 539.125.52:621.039.516/.517
BIBLID: 1451-3994, *23* (2008), 2, pp. 22-27
DOI: 10.2298/NTRP0802022B

[1] Institute for Theoretical and Experimental Physics
25, B. Cheremushkinskaya Str., 117218 Moscow, Russia
[2] Moscow Engineering Physics Institute
31, Kashirskoe shosse, 115409 Moscow, Russia

E-mail address of corresponding author:
geras@itep.ru (A. S. Gerasimov)

tor cell, and the deterministic code ORIGEN-S was used for the calculation of fuel burnup.

CALCULATION RESULTS

The active core of HWPR(Th) is a square lattice of fuel channels placed in a heavy-water tank. The pitch of the square lattice (28.6 cm), the geometry of channels, and fuel assemblies (diameter of assemblies of about 10 cm) were taken to be the same as in reactors of the CANDU type. In both the HWPR(Th) and CANDU reactors the active core is located horizontally and the fuel assemblies move continuously through the active core in opposite directions (bidirection refueling). However, the cell of the active core of HWPR(Th), in contrast to the CANDU reactor, consists of four channels. Three channels are loaded by fuel assemblies $^{232}ThO_2$ with the admixture of $^{233}UO_2$. The amount of ^{233}U in these three channels per unit of length of the cell is 24 g/cm (with no account of structural elements of fuel assemblies such as spacer grid). The fourth channel of the cell is loaded by the target assembly of the same geometry as fuel assemblies. The target assembly in the input of the active core contains only $^{232}ThO_2$ [2]. ^{233}U is accumulated in target assemblies by moving through the active core during fuel cycle. In the output of the core, the target assembly is transformed to a fuel assembly. The self-sufficient mode in HWPR(Th) means that the total amount of ^{233}U in three fuel assemblies of the cell in the input of the active core is equal to the amounts of $^{233}U + {}^{233}Pa$ in all four assemblies of the cell in the output of the active core. Neglecting the losses of fissile nuclei in the reprocessing of spent fuel and fabrication of new fuel assemblies, the reduction of ^{233}U nuclei due to fuel burnup in three fuel channels is compensated by the accumulation of ^{233}U in one target channel of the cell. As an example, the calculation data presented in tab.1 for different burnup W illustrate this compensation for one of the variants of the cell of the active core considered in [2].

It is known for channel reactors that one of the most important parameters mainly determining their nucleus safety is so-called void effect, *i. e.* change of reactivity at the reactor channel dehydration. Calculation comparison of the values and sign of the void coefficient ΔK_{max1} were performed for different variants of channel reactors (in approximation of one cell of the active core) for variation of coolant density in the operating interval of 0.8-0.01 g/cm^3. The results of calculations are presented in tab. 2. Along with ΔK_{max1}, data on ΔK_{max2} are presented, which are calculated in units equal to the fraction of delayed neutrons β_{eff} for fission of ^{235}U, ^{233}U, and Pu. The influence of photoneutrons produced in heavy water at absorption of gamma-ray photons born by fission products and structural materials to ΔK_{max2} was not considered since this would require more detailed calculations with the account of real design of fuel assemblies, geometry and materials of fuel channels and pressure tubes.

Table 1. Content of $^{233}U + {}^{233}Pa$ in four channels of the cell, [%]

Type of assemblies in channels	W [MWd/kg]						
	0	1	2	5	8	11	15
3 channels with fuel assemblies	100	98.4	96.6	92.0	88.3	85.3	82.2
1 channel with target assembly	0	2.20	4.63	9.92	13.4	15.9	18.3

The data of tab. 2 give rise to conclude:

(1) In channel reactors, the change of D_2O coolant by H_2O, ensuring significant economic advantage, leads to essential reducing of nuclear safety of the reactor. This fact is illustrated by comparison of ΔK_{max1} for reactors CANDU and RBMK, in which D_2O and H_2O are used as coolants.

(2) The comparison of different reactors by ΔK_{max1} demonstrates that the minimal increase of reactivity at the dehydration of channels is in HWPR(Th)-2, operating in the self-sufficient mode.

(3) If one is to exclude from consideration a hypothetical RBMK reactor with heavy-water coolant, as well as to pay no attention to technological particularities of reactors, the main conclusion is that the nu-

Table 2. Void effects of reactivity

Characteristic	Type of reactor					
	RBMK-1	RBMK-2	CANDU-1	CANDU-2	HWPR(Th)-1	HWPR(Th)-2
Core cell	Four channels with fuel	Four channels with fuel	Four channels with fuel	Four channels with fuel	Four channels with fuel	Three channels with fuel, one channel with target
Fuel	Uranium, enrichment ^{235}U – 2%	Uranium, enrichment ^{235}U – 2%	Uranium, enrichment ^{235}U – 0.71%	Uranium, enrichment ^{235}U – 1.5%	U-Th, enrichment ^{233}U – 1.5%	U-Th, enrichment ^{233}U – 2.1%
Fissile nuclei	^{235}U	^{235}U	^{235}U	50% ^{235}U; 50% ^{239}Pu	^{233}U	^{233}U
Moderator	Graphite	Graphite	D_2O	D_2O	D_2O	D_2O
Coolant	H_2O	D_2O	D_2O	H_2O	D_2O	D_2O
ΔK_{max1} [%]	4.3	0.69	2.0	6.0	1.3	1.1
ΔK_{max2} [%]	6.3	1.0	2.9	7.9	5.0	4.1

clear safety of considered variants of channel reactors with water coolant, including HWPR(Th)-2 reactor, from the view point of void effect ΔK_{max2}, is approximately of one level.

(4) The reduction of coolant density in channels of a reactor is in most cases accompanied by the increase of power and hence of temperature of fuel elements. Calculations show that the reduction of reactivity due to Doppler effect can compensate the effect of dehydration of channels. However, the result depends on the type of time dependency of a thermal-hydraulic processes occurring in reactor channels during the concrete accident.

The experience of exploitation and accidents of Russian power reactors RBMK, the English reactor SGHWR, and the Canadian reactor GENTILLY-1 [4] confirm that the use of boiling light water in channel reactors as coolant leads, as a rule, to the positive feedback on power and hence to the instability of the whole system. The development and application of a special-purpose regulation system allowed exploitation of a RBMK reactor during a long time in the stable mode. However, in spite of this fact, the accident on Chernobyl NPP occurred due to the coinciding of the variety of events. This accident caused the destruction of the reactor and the release of a big amount of radioactivity in the environment. After this accident, a number of measures was realized at all NPP with RBMK reactors with the purpose to provide their nucleus safety. In particular, the natural mixture of erbium isotopes was added in the fuel of RBMK as a burning absorber. This measure allowed not only to reduce the increase of reactivity at the dehydration of channels but also to change a sign of this effect [5]. As to GENTILLY-1 and SGHWR, after starting and following the exploitation in conditions of high instability these reactors were stopped. In GENTILLY-1, the light boiling water coolant was replaced by nonboiling heavy water, whereupon this reactor was named GENTILLY-2 and was put in exploitation in the CANDU mode.

In the project of the Indian heavy-water channel reactor, natural circulation of light boiling water is used for cooling fuel and target assemblies, that, in principle, should lead to the positive feedback on power. Therefore, the way of deciding on the problem of maintenance of stable power distribution in the active core of this reactor is of great interest. Unfortunately, the available published data are insufficient for the quantitative analysis of nuclear safety of this reactor.

For HWPR(Th) reactor, the addition of mixture of erbium isotopes in fuel elements for reduction of void effect is impossible, since in this case the self-sufficient mode can not be reached. The analysis of balance of neutrons in the HWPR(Th) cell shows that the increase of reactivity at the dehydration of the channel occurs mainly due to the reduction of self-shielding of internal fuel elements in the fuel assembly. Therefore, if all internal fuel elements in the fuel assembly would be replaced by target elements, void factors ΔK_{max1} and ΔK_{max2} would be negative. Therewith, the reduction of number of fuel elements in the fuel assembly does not lead to the considerable reduction of power production during the fuel cycle.

The cell with similar variant of fuel and target accommodation in the fuel assembly (18 fuel elements with ^{233}U in external layers and 19 target elements in internal layers in each of 4 assemblies of the cell) was considered in [1]. It is shown below that the self-sufficient mode can be reached in this case too. According to the methods explained in [2], the analytical relation between multiplication factor K_{cell} and breeding ratio BR can be found

$$K_{cell} = \frac{\nu\beta}{1 + BR + q\beta}$$

where ν is the mean yield of neutrons per fission, $\beta = \Sigma_3^f / \Sigma_3^a$ is the ratio of macroscopic cross-sections of fission and absorption in ^{233}U, and q is the loss of neutrons in structure materials, heavy water, oxygen, ^{233}Pa, and fission products. Values ν and q can be functions of fuel burnup W. The results of calculation of values K_{cell} and then values BR using eq. (1) for four variants of cells and different values of fuel burnup W are presented in tabs. 3 and 4. The relative number N of

Table 3. Values of K_{cell}, BR, and N for variants 1 and 2 composition of cells of the active core contained four channels

	Variant 1 – each channel contains 37 fuel pins			Variant 2 – each channel contains 18 fuel pins and 19 target pins		
Enrichment	1.5% ^{233}U			3% ^{233}U		
W [MWd/kg]	K_{cell}	BR	N [%]	K_{cell}	BR	N [%]
0	1.131	0.921	100	1.116	0.946	100.0
1	1.069	0.961	100	1.069	–	100.2
2	1.057	0.977	99.72	1.061	0.972	99.98
4	1.045	0.983	99.26	1.051	–	99.67
6	1.037	0.987	98.87	1.039	0.994	99.37
8	1.029	–	98.52	1.028	–	99.21
10	1.021	0.991	98.22	1.019	1.003	99.14

Table 4. Values of K_{cell}, *BR*, and *N* for variants 3 and 4 composition of cells of the active core contained four channels

	Variant 3 – three channels contain 37 fuel pins, and one channel contains 37 target pins			Variant 4 – three channels contain 18 fuel pins and 19 target pins, and one channel contains 37 target pins		
Enrichment	2.1% ^{233}U			3.75% ^{233}U		
W [MWd/kg]	K_{cell}	*BR*	*N* [%]	K_{cell}	*BR*	*N* [%]
0	1.068	1.030	100	1.062	1.05	100
1	1.027	1.051	100.81	1.020	1.068	100.87
2	1.030	1.031	100.10	1.022	1.054	101.40
4	1.040	0.992	101.17	–	–	101.82
6	1.045	0.971	100.74	–	–	101.66
8	1.043	0.965	100.09	1.033	0.980	101.26
10	–	–	–	–		100.84

^{233}U + ^{233}Pa as a function of *W* is also given in the tables. It is normalized by 100% in the beginning of the cycle. Fuel pins in the beginning of burnup contain thorium with the admixture of ^{233}U, target pins contain only thorium.

The curves in fig. 1 demonstrate the dependence of *BR* from K_{cell} for four variants of cells, while the increasing values of *W* serve as the parameter. The curves in fig. 2 show dependence *N*(*W*). The irregularity of curves 3and 4 in fig. 1 is explained by the deformation of the neutron spectrum due to the difference in processes of burning and accumulation of ^{233}U in the cell. For the four considered variants, the region of operating points exists, in which $K_{cell} > 1$and $BR > 1$. The curves 3 and 4 in fig. 2 demonstrate that the self-sufficient mode ($N > 100\%$ for $W > 0$) is possible only for variants 3 and 4 of the cell. However, the additional calculations demonstrated that the void coefficients ΔK_{max1} and ΔK_{max2} are negative only for the fourth variant of the cell.

These results, in our opinion, demonstrate the practical feasibility of the self-sufficient mode of operation in a heavy-water channel reactor with the negative void coefficient. As one would expect, the increase of reactor safety level almost always leads to complication of its design. In the considered event this complication is the application of combined fuel assemblies containing simultaneously both fuel and target elements. This will inevitably complicate exploitation and particularly the processes of assembling and disassembling.

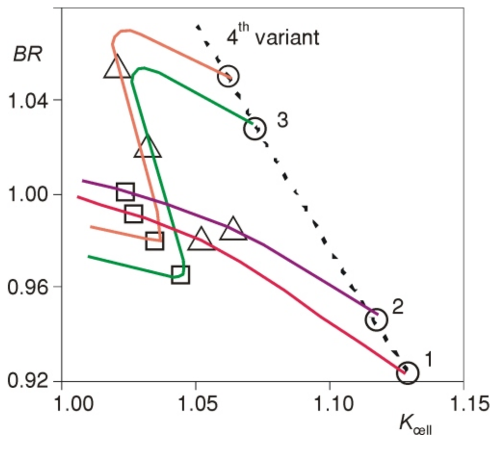

Figure 1. Dependence of *BR* on K_{cell} for four variants of the elementary cell of the active core. Marks on the curves indicate *W* values: ○ *W* = 0, △ *W* = 2, □ *W* = 8 MWd/kg

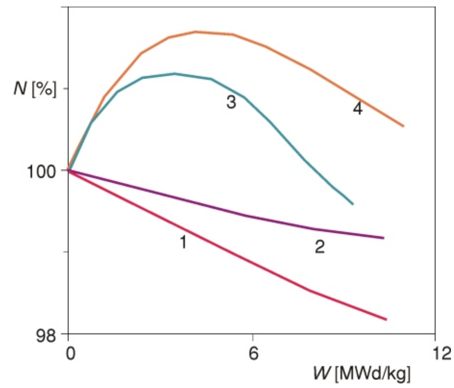

Figure 2. Dependence of number *N* of ^{233}U + ^{233}Pa on fuel burnup for four variants of the elementary cell of the active core

Now to proceed with the consideration of emergency situations and deviation from the operating parameters of HWPR(Th) reactor (corresponds to HWPR(Th)-2 in tab. 2), which can lead to the increase of reactivity. The analysis was done for one separated cell of the active core of the reactor and fuel burnup $W = 0$.

(1) The data in tab. 5 present the dependency of the multiplication factor K_{cell} and the reactivity factor $dK_{cell}/d\rho$ from variation of D_2O density ρ in channels due to changing the temperature of D_2O coolant or its boiling. The reason of that can be the failure of the system of automatic maintenance of operating temperature and the fault in the system of cooling of the coolant.

The data presented in tab. 5 demonstrate that $dK_{cell}/d\rho$ in HWPR(Th) reactor is positive for the

Table 5. Multiplication factor depending on coolant density and reactivity effects

	Density of D_2O in channel ρ [g/cm^3]			
	0.8	0.48	0.16	0.01
K_{cell}	1.0664	1.0714	1.0744	1.0774
$dK_{cell}/d\rho$	+1.56	+0.94	+2.0	–

whole interval of coolant density. In the beginning of the process $dK_{cell}/d\rho$ decreases, while in the end it increases to the value exceeding the initial value. At full dehydration of the channels (from operating density ~0,8 g/cm^3 to 0), the increase of reactivity is 1.1%. This value is in agreement with the value of the void factor in tab. 2.

(2) The data in tab. 6 present the dependency K_{cell} on the water density in the space between the channels of the reactor because of changing the temperature of the coolant due to different kind of faults in the cooling system. These data demonstrate that the increase of temperature of the coolant leads to the decrease of reactivity in HWPR(Th). In particular, this fact points to the possibility to increase fuel burnup in HWPR(Th) by means of small changing the lattice step.

Table 6. Multiplication factor depending on moderator temperature in heavy-water tank

	D_2O temperature in heavy-water tank, [°C]				
	50	100	120	150	170
D_2O pressure [atm]*	1.11	1.98	2.95	4.75	8.0
D_2O density [g/cm^3]	1.1	1.06	1.05	1.02	1.00
K_{cell}	1.066	–	1.067	–	1.065

*1 atm = 101325 Pa

(3) The data in tab. 7 present the change of K_{cell} at the ingress of light water in the heavy-water coolant or in the heavy-water moderator. The slow increase of H_2O concentration in D_2O can occur in any heavy-water reactor because of the stop or fault of rectification installation. In heavy accidents with the destruction of circuit of cooling of moderator or coolant, light water can permeate into heavy-water circuit practically instantly.

These data demonstrate that at the ingress of light water in a heavy-water coolant and moderator the multiplication factor decreases. Since at the ingress of light water in the circuit of cooling of the coolant the change of K_{Cell} is low, it is possible to use for this purpose heavy water with the admixture of light water less than ~5%, which will simplify the operation of rectification installations.

Table 7. Multiplication factor depending on ingress of H_2O in D_2O in coolant or in moderator

H_2O in coolant [%]	0	0.5	1.0	2.0	10.0
K_{cell}	1.068	1.066	1.066	1.066	1.062
H_2O in moderator [%]	0	0.5	1.0	2.0	10.0
K_{cell}	1.068	1.057	1.043	1.015	0.834

CONCLUSIONS

On the basis of the performed calculation studies, it is possible to conclude that the nuclear safety of HWPR(Th) is at least on same level as the use-proved nuclear safety of reactors of the CANDU type. The application of compound fuel assemblies containing fuel and target elements in HWPR(Th) (variant HWPR(Th)-2 in tab. 2) ensures a negative value of the void factor. In comparison with a reactor of the CANDU type, such power reactor operating in the self-sufficient mode has a much higher nuclear safety level.

As for the radiation safety of HWPR(Th), it is mainly determined by the long-term radiotoxicity and decay heat power of the spent fuel reloaded from the reactor. The calculation of the appropriate characteristics was made in [6, 7]. The results of calculation demonstrated that the radiotoxicity of spent fuel reloaded from the reactor operating in U-Pu fuel cycle exceeds the radiotoxicity of reloaded thorium fuel by 8 times in 4 years after reloading, by 6 times in 100 years, and by 300 times in 1000 years after reloading. Similarly, the decay heat power of spent U-Pu fuel exceeds the decay heat power of spent thorium fuel by 6 times in 4 years after reloading, by 3 times in 100 years, and by 60 times in 1000 years after reloading. This difference in the levels of radiotoxicity and decay heat power for U-Pu and thorium spent fuel is explained mainly by a very low amount of isotopes of Pu, Np, Am, and Cm in thorium spent fuel. Only if we consider a hypothetic operation of these reactors in the closed fuel cycle during many thousand years, the isotopes of Pu, Np, Am, and Cm would be accumulated in thorium fuel in similar amounts as in U-Pu fuel, and the radiation danger of both types of fuel would be of the same level.

In summary, the calculation study presented in this paper demonstrates practical feasibility of the development of nuclear and radiation safe power reactor operating in the self-sufficient thorium-uranium mode.

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Борис Р. БЕРГЕЛСОН, Александар С. ГЕРАСИМОВ, Георгиј В. ТИХОМИРОВ

НЕКА ПИТАЊА НУКЛЕАРНЕ СИГУРНОСТИ ТЕШКОВОДНИХ ЕНЕРГЕТСКИХ РЕАКТОРА СА САМОДОВОЉНИМ ТОРИЈУМОВИМ ЦИКЛУСОМ

У овом раду начињени су упоредни прорачуни коефицијента шупљине за различите врсте каналних реактора са густином хладиоца у опсегу 0.8-0.01 g/cm^3. Ови резултати показали су да код тешководних каналних реактора замена D_2O хладиоца H_2O хладиоцем, осигуравајући значајне економске предности, води ка битној редукцији нуклеарне сигурности постројења. Поређење различитих реактора према коефицијенту шупљине показује да је при дехидрацији канала пораст реактивности минималан код HWPR(Th) реактора који раде у самодовољном моду. Смањење густине хладиоца у каналима праћено је у многим случајевима порастом снаге и температуре горивног склопа. Прорачуни показују да смањење реактивности услед Доплеровог ефекта може да надомести ефекте дехидрације канала. Међутим, резултати зависе од временски зависних топлотнохидрауличких процеса који настају у реакторским каналима у специфичном акциденту. Резултати добијени у раду потврђују да је нуклеарна сигурност HWPR(Th) реактора на истом нивоу као нуклеарна сигурност КАНДУ реактора која је потврђена у пракси.

Кључне речи: торијумов горивни циклус, КАНДУ реактор, нуклеарна сигурност