STUDY AND CHOICE OF MAIN CHARACTERISTICS OF FAST REACTOR - EFFECTIVE MINOR ACTINIDE BURNER

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Abstract

This paper presents the principal design and performance data of advanced fast power reactor core for plutonium and actinides burning. Some information concerning the Russian programme of plutonium utilization are also presented.

INTRODUCTION

Basic feature of fast reactors-ability to transfer nuclear power into self-supplying regime with nuclear fuel -has been scientifically justified and technically verified at demonstration NPPs and nuclear fuel cycle enterprises.

But at the present stage of nuclear power development, when sufficient uranium reserves exist, this feature of fast reactors is not topical and could be called for in some decades.

At the same time the basic features of fast reactors and the experience gained in designing and operation of NPPs with a fast reactors allow to state that NPPs of this type can be effectively used for combined and safe solution of power and ecological problems using accumulated plutonium and decreasing quantity of radiotoxical products of nuclear fuel cycle -burning of minor actinides.

When designing nuclear power installation with above mentioned functions the following should be provided :

- competitiveness with light water and other reactor types in electricity cost,
- high safety level without evacuation of population from adjacent to the NPP installed power utilization (with maximum use of proved technical solutions).

Below some ideas on choosing of major parameters of fast reactor - effective actinides burner are presented

1. UNIT POWER

Reactor power choosing is one the crucial issues of designing.

Unbiased decision of this issue can be obtained only by combined accounting for the results of technical-economical optimization of the basic technical solutions, the design and operation experience of operating NPPs, the applicability of the NPP being developed for the power network.

Power range, in which the practical realization of a power unit with the above mentioned target is possible, is quite wide - from 200 MW(e) to 1600 MW(e).

In this case the following factors are accounted for.

The most important factor is reactor self-protection, which is characterized by the ability to prevent destruction or melting of the core in severe beyond design accidents due to inherent safety features (SVRE≤0), emergency cooling under conditions of sodium boiling) and using of passive means of action on reactivity. The analysis shows that for traditional cores with the power increase, all other factors being the same, the attainment of equal level of self-protection is more difficult (Fig.1). The question whether this tendency would be conserved foe special cores require a more detailed analysis.

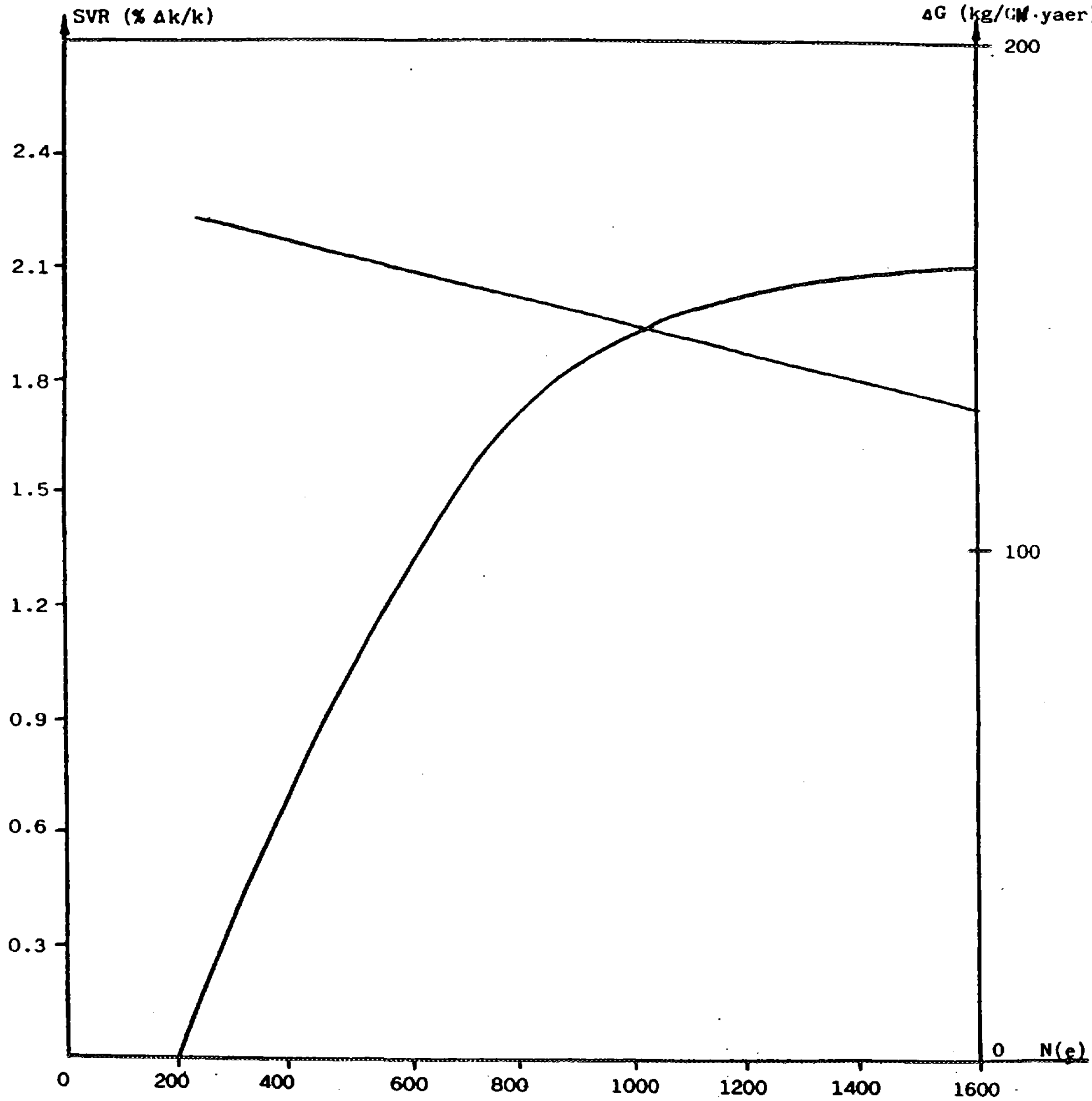

Fig.1. Dependence of SVR and plutonium burning efficiency on reactor power

Reactor power and core volume increase, other parameters being the same, is accompanied by decrease of the neutron leakage and the spectra softening. As a result fuel enrichment and actinide burning effectiveness decrease (Fig.1). Assessments show that increase of reactor power from 800 MW(e) to 1600 MW(e) with the same approach to the core design (decreasing of fuel volume fraction and use of absorbing assemblies) would lead to decrease of plutonium specific burning out effectiveness by 15 %. Average fission cross section of threshold nuclides (Pu-240, Np, Am etc.) also decrease by 10-15%.

2. CHOOSING OF CORE PARAMETERS

2.1. Possible ways of realization of reactor core.

Analysis of fast reactor possibilities for effective actinide burning shows that oxide fuel wholly corresponds to this goal. Oxide fuel has the least breeding among others, more dense fuels types, have been much studied and mastered. More effective for burning fuel -without uranium-238 with inert matrix - still requires long-term and comprehensive studies and can not be laid to the basis of the project.

Preliminary investigations of various core types have shown that it is necessary to renounce breeder blanket and to increase the plutonium enrichment up to 45 %. The main problem in search of optimal core configuration consists in searching of the most correct ways of fuel enrichment increasing corresponding to various requirements in reactor physics and safety.

The numerous studies have shown that the plutonium enrichment increasing can be attained by two ways [1] :

- by introduction of absorbing materials into the core,
- by reducing of fuel volume fraction.

Some ways of fast reactor core realization for effective actinide burning can be demonstrated by the example of three core types as applied to the BN-800 reactor project.

a) Core in design dimensions (565 SAs). Enrichment increase is obtained by introducing absorber assemblies on the base of natural boron carbide and some decreasing of fuel volume fraction using fuel pins will less diameter (6.0*0.4 mm). Absorbing assemblies are located uniformly in the centers of 48 modules, consisting of 7 SAs to which subzones of middle (MEZ) and high (HEZ) enrichment are divided (Fig.2). The power level is hold due to core height increase up to 105-110 cm. Maximum plutonium burning effectiveness is characterized by value 342 kg/year (61.1 kg/TW*h).

b) Core is extended one SA row in the radial blanket (655 SAs total, Fig.3). Enrichment increase is obtained only by decrease of fuel volume fraction and introducing of absorbing blankets from natural boron carbide. Maximum effectiveness of plutonium burning at fuel pin diameter 6.0*0.5 mm with increased central hole is 400 kg/year (71.4 kg/TW*h)

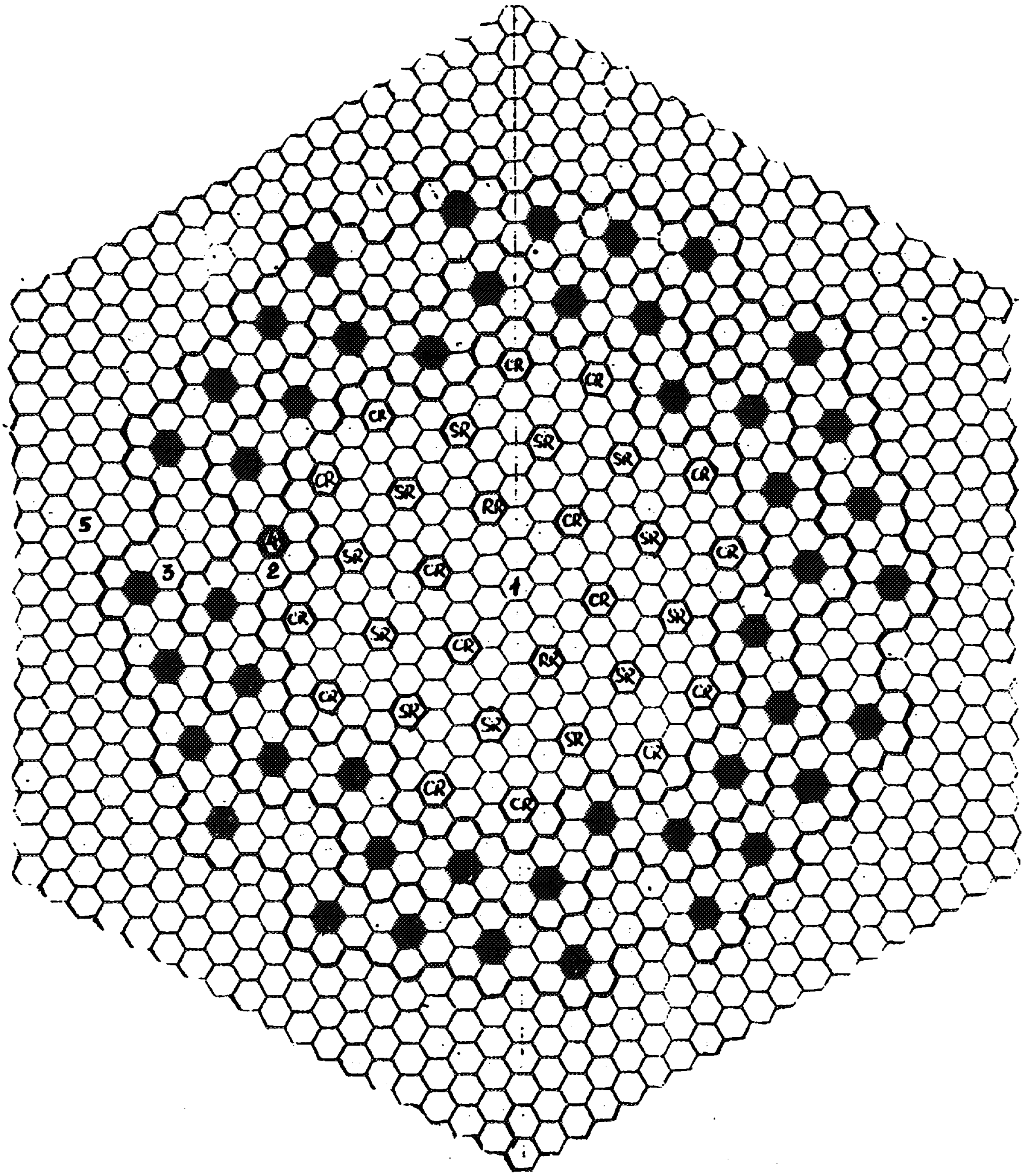

Fig.2 Core Layout with Absorber Subassemblies

1-LEZ SA	5- Steel blanket
2-MEZ SA	SR- safety rod
3-HEZ SA	CR- compensating rod
4-Absorber subassembly	RR- regulating rod

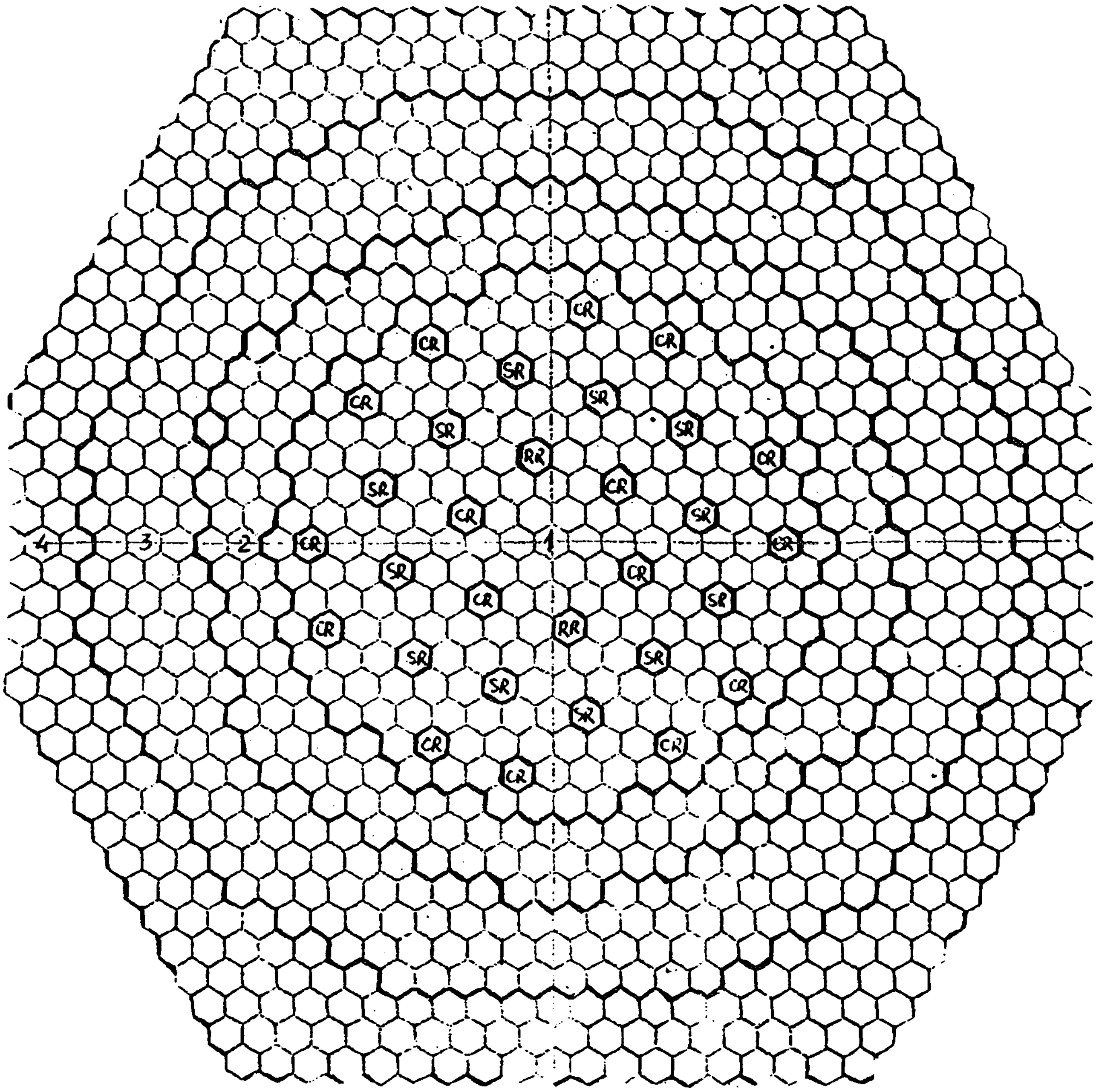

Fig.3 Core Layout with Increased Radius and Fuel Pins Diameter
6.0*0.5 mm

1- LEZ SA
2- MEZ SA
3- HEZ SA
4- Absorber blanket

SR- Safety rod
CR- Compensating rod
RR- Regulating rod

c) The core is extend one as far as outer boundary of the in-reactor storage (IRS) and totals 900 SAs. Maximum effectiveness of plutonium burning is 490 kg/year (87.0 kg/TW*h), but maximum fuel enrichment begins to exceed noticeably the prescribed standard 45 %.

Detailed date on the studies carried out are presented in Tables 1, 2, 3.

2.2 Results analysis

Analysis of the results obtained and possible technical decisions allows the following conclusions.

a) Enrichment increase through introduction of absorbing SAs into the core allows to attain the sufficiently high plutonium burning characteristics. However, such way have some disadvantages, the main of them is substantial non-flattering of power distribution, connected with great amount of absorber sub-assemblies. Some difficulties are connected with the zero sodium void effect achieving because of substantial core height increasing.

The last problem can be solved by using of absorbing blankets instead of steel ones, although such cores require the additional investigations.

b) Enrichment increase by means of fuel volume fraction decreasing give the good plutonium burning characteristics. The disadvantage of such way is core dimensions increasing .

Using the absorbing blankets from boron carbide substantially decreases the SVRE value in the core, opening the additional possibilities for the minor actinide burning.

Using of fuel pins with increased diameter of central hole in the fuel pellets requires to solve a number of technological problems, connected with fuel pellets manufacturing and problems of mechanical and radiation stability of such pellets.

Increasing the core dimensions on 90 sub-assemblies for the BN-800 reactor project will require the re-design of lower collector, but this problem is wholly solved.

c) More significant increase of SA number in the core (up to 900) allows even more to decrease the fuel volume fraction (on 50-70%) and increase effectiveness of plutonium burning up to 87 kg/TW*h.

However, the substantial exceeding of admissible plutonium enrichment limit (45%) in those cores, the necessity of substantial re-design of in-vessel structure make such way of core design not rational.

Proceeding from the above, the most optimal variant from various points of view is the core with 665 SAs and fuel pin with diameter 6.0*0.5 and central hole, which diameter is equal 0.5 of fuel pellet diameter. Such dimensions correspond to the fuel volume fraction $\varepsilon=0.2$.

Table 1

Core versions with absorber introduction

	Fuel pin 6.6*0.4 (ε_{fuel}=0.335			Fuel pin 6.0*0.4 (ε_{fuel}=0.269		
Number of SA	48	48	48	48	48	48
Absorber volume fraction, %	0	20	60	0	20	60
Number of fuel SAs in core	517	517	517	517	517	517
Core height, cm	105	110	110	105	110	110
Fuel enrichment by zones						
LEZ	19.4	17.7	19.2	23.2	21.2	23.0
MEZ	22.0	27.2	29.5	26.4	33.1	36.0
HEZ	27.0	35.9	38.0	32.3	41.4	45.0
Core SVRE %Δk/k	+2.10	+1.44	+1.41	+1.84	+1.34	+1.19
Quantity of burned plutonium,						
kg/yr	190	254	276	230	310	342
kg/yr GW(e)	238	318	345	288	388	428
kg/ TW*h	33.9	45.3	49.2	41.1	55.4	61.1

Table 2

Core versions without absorber with fuel pins 6.6*0.4

	Variant				
	1	2	3	4	5
SA number in core	565	565	655	900	900
Fuel pin number in SA	127	127	127	91	91
Fuel volume fraction	0.335	0.335	0.335	0.240	0.160
Core height, cm	100	100	80	85	130
Blanket material	steel	natural boron carbide	natural boron carbide	natural boron carbide	natural boron carbide
Fuel enrichment by zones					
LEZ	17.5	19.6	20.1	26.7	28.4
MEZ	19.7	22.1	22.7	29.7	31.6
HEZ	24.3	27.2	27.9	36.5	38.8
Core SVRE %Δk/k	+2.03	+0.87	+0.41	-0.61	+0.45
Quantity of burned plutonium,					
kg/yr	146	195	209	273	370
kg/yr GW(e)	183	244	261	342	465
kg/ TW*h	26.1	34.6	37.1	48.5	66.0

Table 3

Core versions without absorber with fuel pins 6.0*0.4 mm and 6.0*0.5 mm and absorbing blankets from natural boron carbide

	Variant					
	1	2	3	4	5	6
SA number in core	655	655	655	900	900	900
Core height, cm	85	85	85	85	130	130
Fuel pin number in SA	127	127	127	91	61	61
Fuel pin diameter*cladding thickness, mm	6.0*0.4	6.0*0.4	6.0*0.5	6.0*0.4	6.0*0.4	6.0*0.5
Relation of central hole diameter to fuel pellet diameter	0.3	0.5	0.5	0.3	0.3	0.5
Fuel volume fraction	0.27	0.22	0.21	0.19	0.13	0.10
Fuel enrichment by zones						
LEZ	24.8	31.6	34.2	32.1	34.6	37.5
MEZ	28.1	35.8	38.7	36.4	39.2	42.5
HEZ	34.5	44.0	47.6	44.6	48.0	52.0
Core SVRE %Δk/k	-0.7	-1.3	-1.5	-3.0	-1.4	-1.6
Quantity of burned plutonium,						
kg/yr	332	371	400	412	457	489
kg/yr GW(e)	414	463	500	515	571	611
kg/ TW*h	58.9	66.2	71.4	73.2	81.3	87.2

3. THE MAIN PRINCIPLES OF PLUTONIUM UTILIZATION PROGRAM IN RUSSIA.

Accumulated stocks of extracted power plutonium together with expected receiving significant amount of weapon-grade plutonium in result of disassembling of nuclear weapon requires the developing of certain strategy of plutonium handling including safety, economic, ecology issues and regime of unspreading.

Conception of MinAtom of plutonium handling is based on following main principles [2]:

- maximum using of accumulated experience of plutonium handling;
- reliable protection against diversion and uncontrolled utilization of plutonium ;
- acceptability with point of view of ecology and in interests of environment;
- possibility of using of existing basis for development of optimal fuel cycle with long-term perspective;

Now it has been considered three possible directions of plutonium utilization :

- using of PO "MAYAK" (radiochemical facility, facility for MOX fuel production, NPP with BN-800 reactor);
- using of existing reactors (BN-600, modern unit of VVER-1000);
- using VVER-1000 reactors planning to construct.

Comparative estimations of above-mentioned directions show that the first direction is most preferable for following reasons:

- in the directions № 1 it is realized the conception of closed nuclear - power center where it is more simple to solve the problem of prevention of plutonium using without sanctioning;
- the using only existing reactors (fast reactor BN-600 and 4 units of thermal reactors VVER-1000) doesn't allow to utilize wholly plutonium which is expected to receive;
- the development of nuclear power engineering in the third direction requires the introduction of the additional power units whose capacity should be in 3 times more than one in variant with fast reactors.

The characteristics of BN-800 fast reactor and reactor for Pu burning ("burner") on the base of BN-800- type reactor from point of view of utilization (transformation into the form of spent fuel) and burning (physical destruction) with simultaneous using of energy potential of plutonium are given in the Table 4.

The table 4 shows that the BN-800 type core modernized for effective plutonium utilization allows to expand significantly the possibilities of this reactor for states where it is necessary both utilization and burning of plutonium as nuclear material.

It is interesting in some extent to consider the possibilities of fast reactor work in the system with VVER-type reactors.

For study of thermal and fast reactors system work feasibility in closed fuel cycle we will consider the simplified scheme of this system given on the Fig. 4.

Plutonium together with minor actinides produced in two VVER is mixed with spent BN-800 reactor fuel, from which the fission products are removed, and comes again into the fast reactor core.

After multi-recycle according to the above-mentioned procedure in the fast reactor core the quasistationary isotopic composition of actinides is formed.

The isotopic compositions of actinides of unloading VVER fuel and quasistationary composition of ones after multi recycle in the fast reactor core are given in the Table 5.

Thus, in the isotopic composition of actinides (plutonium + minor actinides) the minor actinides fraction increases approximately in 1.5 times that corresponds to the content of minor actinides in the fresh fuel of fast reactor on the level of 3-4 %.

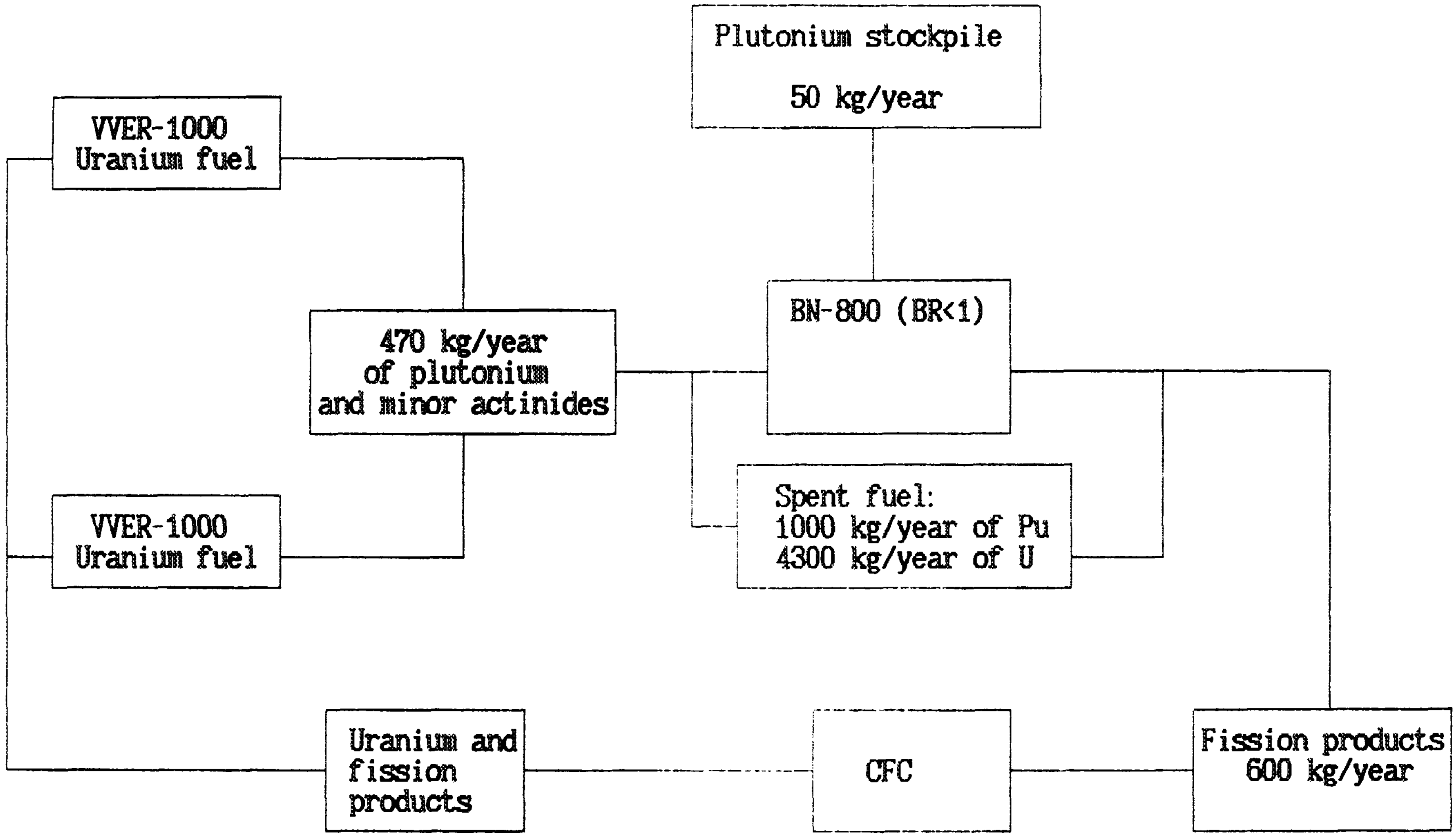

Fig. 4. Scheme of thermal and fast reactors system, working in closed fuel cycle.

So in this scheme it is taken place the effective plutonium utilization as well as minor actinides. From point of view of the ecology it is obvious the efficiency of nuclear power engineering work in accordance with above-described principle.

Table 4

Characteristics of BN-800 reactor project and BN-800 reactor-burner

Parameter	BN-800	BN-800 'burner'
Pu loading in the reactor, kg/yr	1600	1400
Pu unloading from the reactor, kg/yr	1600	1000
Burnt Pu in the core, kg/yr	600	600
Pu produced in the blanket, kg/yr	150	0
Pu produced in the core, kg/yr	450	200

Table 5

Isotopic composition of actinides in discharged fuel of VVER and in the fuel of BN

Isotope	Isotopic composition of actinides	
	Unloading VVER fuel	Quasistationary composition
Pu-238	1.2	2.4
Pu-239	51.7	45.4
Pu-240	22.6	30.8
Pu-241	11.7	6.3
Pu-242	5.4	6.1
Np-237	3.0	1.6
Am-241	2.7	4.9
Am-242m	-	0.2
Am-243	1.1	1.7
Cm-244	0.4	0.6

CONCLUSION

1. The using of fast reactor in the nuclear power engineering system allows to solve power and ecological problems by means of effective plutonium and minor actinides utilization.

2. Analysis shows that for medium capacity reactors (BN-800 type) it is possible to develop a core with MOX fuel for effective plutonium utilization on the base of using of fuel pin structure with low fuel volume fraction and increased enrichment of plutonium and also using of absorber shield.

It is provided a high safety level (optimal Doppler- effect and close zero or negative value of SVRE).

3. Considered scenarios of plutonium utilization show that fast reactors using in the closed nuclear-power centers system fully in Russia satisfies the requests of effective plutonium using and with simultaneous solution of unspreading problem.

4. Advanced core of BN-800-type reactor from point of view of increasing of plutonium utilization allows in the conditions of thermal and fast reactors to solve the problem of spent fuel radiotoxicity reduction by means of including produced actinides into fuel cycle.

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