CORE DESIGN AND FUEL CYCLE OF ADVANCED FAST REACTOR WITH SODIUM COOLANT

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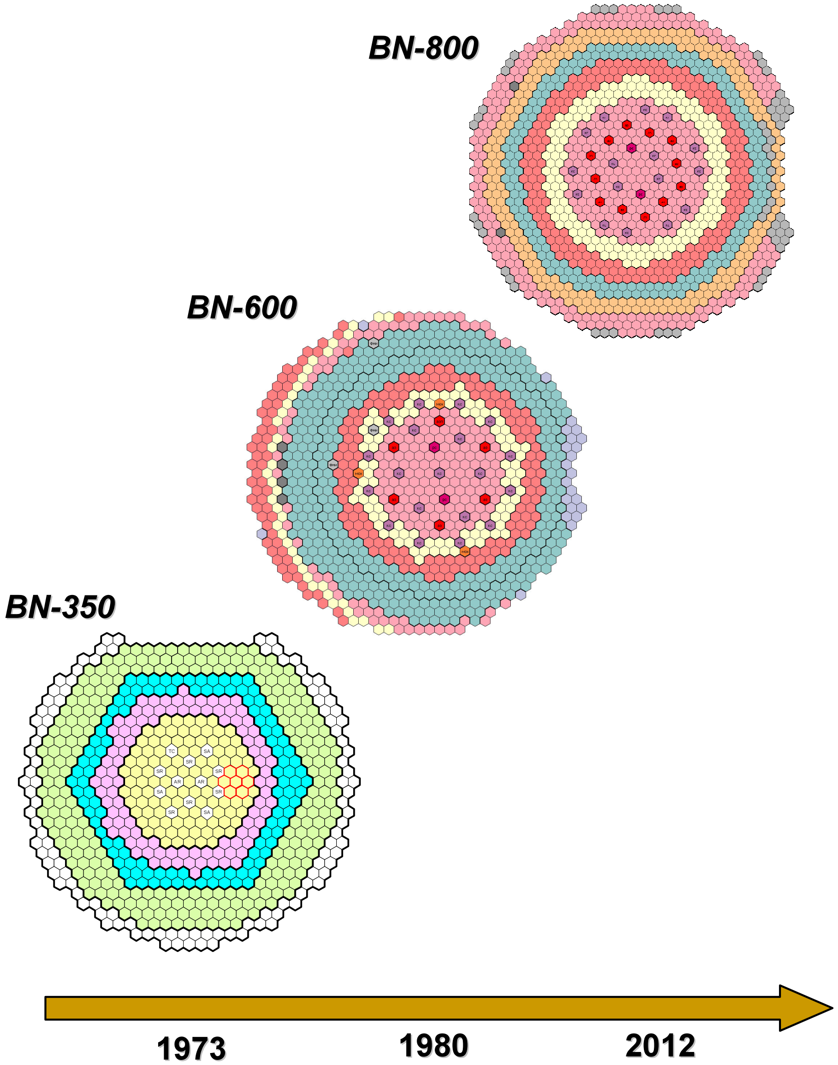
International Conference on Fast Reactors and Related Fuel Cycles (FR09) - *Challenges and Opportunities* -
December 7 - 11, 2009, Kyoto, Japan

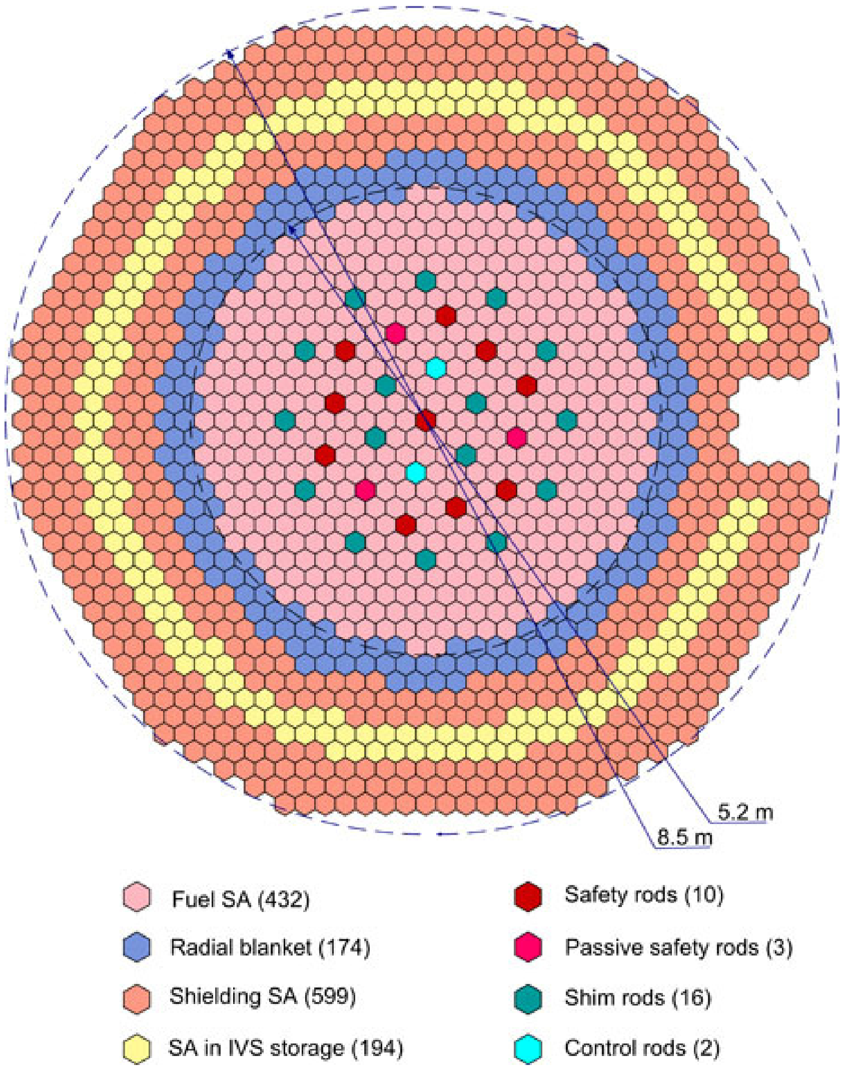
Main tasks under development of BN-1200 core



BN-1200

- ***Improvement of technical and economic indicators:***
  - Optimization of design and decrease in capital expenses
  - Decrease in expenses for fuel, increase in the maximum burn-up
  - Increase in load factor
- ***Safety perfection:***
  - Improvement of self-protection properties
  - Use of systems of passive safety
- ***Solution of fuel cycle problems:***
  - Resource problem of nuclear power at the expense of effective breeding
  - Ensuring of ecological attractiveness of fuel cycle at the expense of:
    - cardinal solution of spent nuclear fuel problem of thermal and fast reactors and
    - Minimization of amount of radioactive waste

Core configuration



✓ ***Principle feature of BN-1200 core – low power density ~230 MW/m^3, that in ~2 times lower than in the previous projects***

Configuration features:

- Geometry and sizes:
  - Core diameter ~5.2 m is defined by the chosen power and specific power density
  - Core height ~0.85 m is chosen proceeding from ensuring SVRE and density reactivity effect values close to zero
  - H/D~0.16 – “flat core”
- Single-enrichment smoothing of power profile in core (in the previous projects - three-enrichment smoothing)
- Spacious in-vessel storage (IVS). Spent fuel subassemblies are kept in the IVS during two refueling intervals ~2 years enabling direct unloading of SA
- Radiating shield from natural boron carbide

Fuel subassembly, control and safety system

Main technical characteristics of core SA

Characteristics	BN-1200	BN-800
Wrapper across flat width and wall thickness, mm	181×3.5	96.0×2.0
Cladding / wrapper material	Ferritic steel	Austenitic / Ferritic steel
Number of fuel pins per SA	271	127
Cladding diameter and thickness, mm	9.3×0.6	6.9×0.4
Effective density of fuel, g/cm^3	9.2	8.6
Core height, mm	85	88
Sodium plenum height, mm	400	300
Height of upper boron shielding, mm	650	150
Material of lower axial blanket, mm	UO_2	UO_2
Effective density of axial blanket material, g/cm^3	9.5	9.2
Height of lower axial blanket, mm	400	350

✓ ***Essentially increased fuel pin diameter and SA size***

✓ ***Increased density of fuel***

✓ ***New cladding material – ferritic steel***

Control and safety system

- 16 shim rods (SHR) for compensation of reactivity change caused by the fuel burn-up during reactor operation;
- 2 control rods (CR) for automatic control and maintaining reactor power during its operation;
- 10 safety rods (SR) for urgent decrease of reactor power and making reactor subcritical in case of abnormal operating conditions.

  4 safety rods from them use passive principle of operation - temperature sensing element, responding at excess of temperature ~800 °C and providing rod dump into core;
- ***3 passive safety rods for urgent decrease of reactor power at reduction of coolant flow rate.***

Core parameters: fuel and CBR

Reactor Power (thermal /electric), MW	BN-1200 2900 / 1200		BN-800 2100 / 880
Fuel	oxide	nitride	oxide
Average power density in the core, MW/m^3	230	230	450
Fuel volume fraction	0.47	0.47	0.43
Fuel effective density, g/cm^3	9.2	11.5	8.6
Core breeding ratio (CBR)	0.89	1.04	0.73

✓ ***BN-1200 core is capable of using both MOX and nitride fuel without changes of the other reactor elements as nitride fuel is assimilated, and depending on proved fuel performance:***

- ***reliability***
- ***burn-up and***
- ***cost***

- An important role in optimization of BN-1200 parameters is played by the increase of stability of core properties by the increase of the core fuel breeding ratio (CBR) compensating fuel burn-up, since this causes the following advantages:
  - stability of core reactivity
  - stability of neutron field
  - increase of total BR

Increase of CBR in BN-1200 is achieved by the following measures:

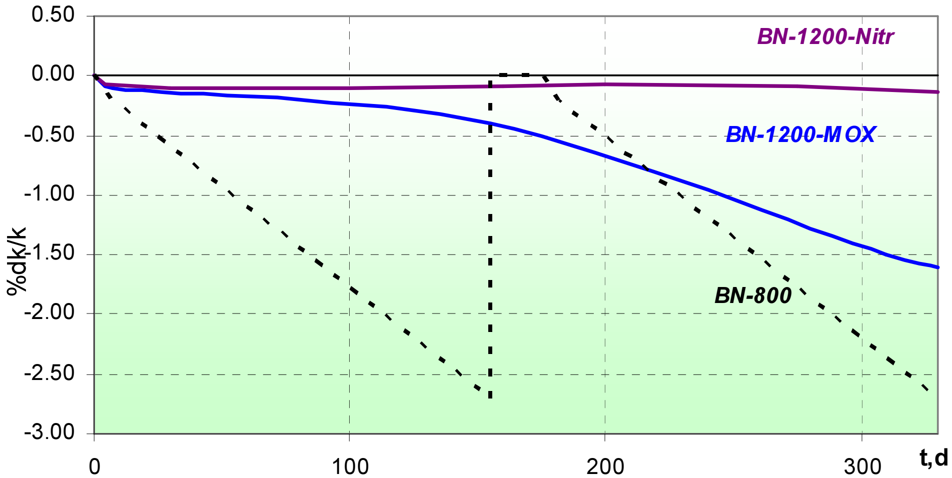
- increase of fuel volume fraction from 0.43 to 0.47
- Increase of effective density of MOX fuel from 8.6 g/cm^3 (BN-800) to 9.2 g/cm^3

or

- use of high-density nitride fuel

Core characteristics: reactivity effects, reactor run and load factor

Reactor Power (thermal /electric), MW	BN-1200 2900 / 1200	
Fuel	oxide	nitride
Fuel lifetime, year / Refueling ratio	5 / 5	4 / 4
Average power density in the core, MW/m^3	230	230
Core breeding ratio (CBR)	0.89	1.04
Refueling interval	1 year	1 year
Excess reactivity for fuel burn-up	1.9 330 days	0.2 330 days



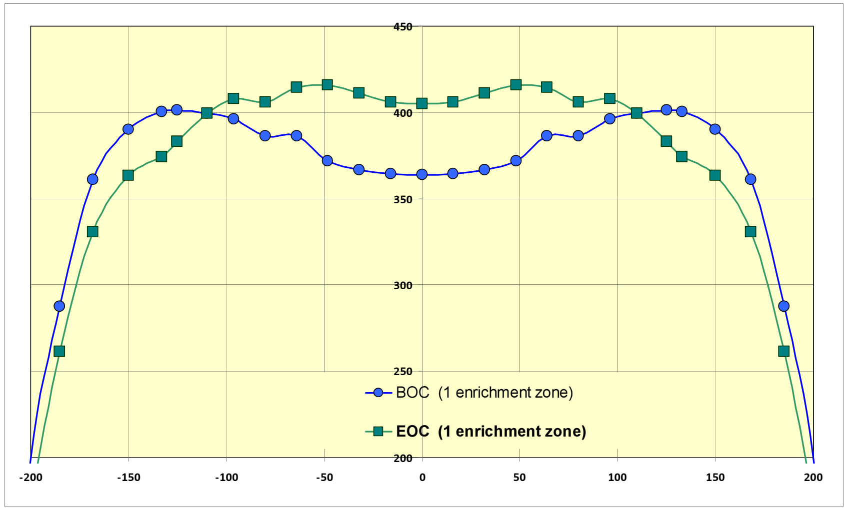
Inherent safety properties:

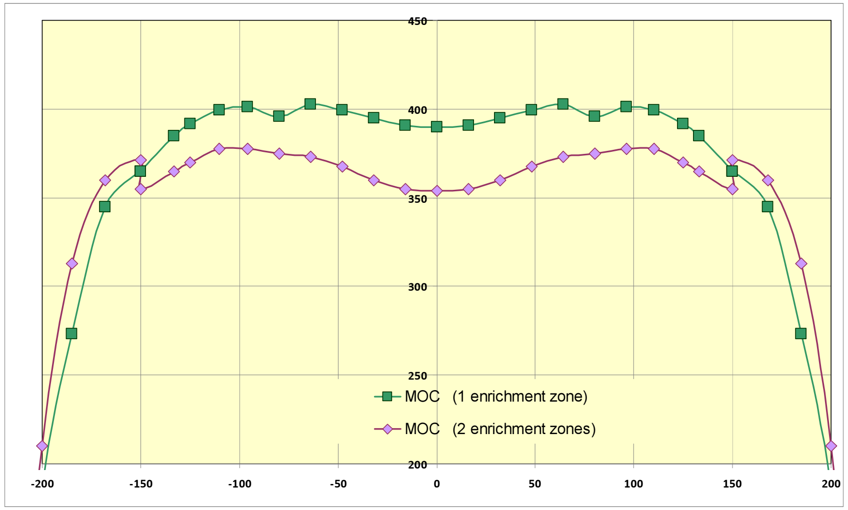
- All reactivity effects appearing under normal operating conditions, abnormal operating conditions and in cases of design basis accidents are not positive and these assure negative feedbacks
- Reference core concept assures "zero SVRE" manifested in beyond design basis accidents
- In BN-1200 reactivity is much more stable owing to decrease to zero of the fuel burn-up reactivity effect

Conclusions:

- ✓ ***Studies have shown the possibility of decreasing excess reactivity of operating reactor below $\beta_{eff.}$, thus eliminating reactor runaway on prompt neutrons***
- ✓ ***Increase of refueling interval up to 1 year (in comparison with 6 months in the previous designs)***
- ✓ ***Increase of reactor load factor up to 0.9 value***

Core characteristics: power rate distribution





- In the cores of BN-600 and BN-800 reactors, optimality of multi-zone smoothing (LEZ, MEZ and HEZ) was demonstrated
- Increase of core dimensions and its lifetime hinders stabilization of time and spatial power distribution
- This problem is solved by the following measures:
  - increase of core BR
  - decrease of enrichment zones number

Results:

- In reference core, proper power rate distribution was reached in the simplest (single-zone) option. The given variant has advantages by control rods worth and SVRE.
- Double-zone approach is investigated. According to the first estimates, max power rate is decreased by ~10% and fuel element cladding temperature is decreased by ~10ºC
- ✓ ***As the main variant it is accepted single-enrichment smoothing of power profile in core***
- ✓ ***Max. linear power of fuel element does not exceed 45 kW/m***

Core characteristics: fuel burn-up and radiation damage of materials

Reactor Power (thermal /electric), MW	BN-1200 2900 / 1200	
Fuel	oxide	nitride
Fuel lifetime, year / Refueling ratio	5 / 5	4 / 4
Refueling interval	1 year	1 year
Max fuel burn-up, % h.a.	17.2	11.4
Average fuel burn-up, % h.a.	11.6	6.7
Max fuel element cladding dose, dpa	164	133
Max temperature of fuel element cladding, °C	665	665
Coolant temperature rise	140	140
Annual fuel consumption, tons h.m./GW	7.3	12.6
Annual Pu consumption , tons h.m./GW	1.2	1.6

- High fuel burn-up (up to ~17% h.a.)
- New level of radiation damage of materials – up to ~160 dpa

This is achieved:

- by the use of ferritic steels
- in order to compensate for insufficient high-temperature strength of existing steels, cladding temperature is decreased down to 660-670°C by reduced coolant heating and increasing quality of power rate profiling

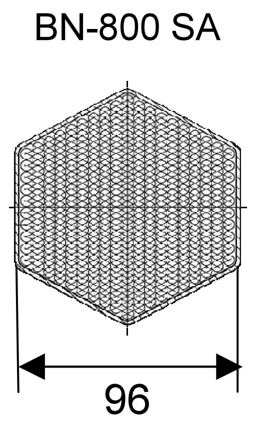
Conclusions:

✓ ***increase of fuel burn-up causes decrease of Pu consumption by almost factor of 2 and fuel consumption by 40%, as compared with those of BN-800 reactor***

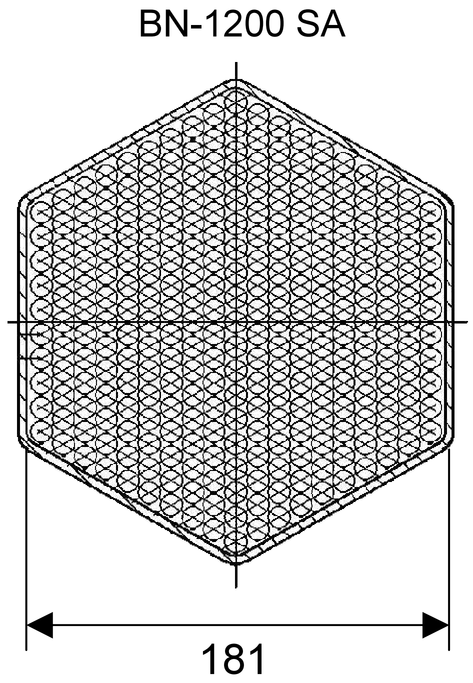
✓ ***increase of fuel burn-up will be carried out step-by-step with use at the first stages of modern structural materials***

✓ ***successful development of the new types of oxide dispersion strengthened high-temperature steels would allow additional increase of fuel burn-up till ~20% h.a.***

Improvement of technical and economical characteristics by core design optimization



Annual consumption
460 SA/GW
58000 fuel pins/GW



Annual consumption
71 SA/GW
19000 fuel pins/GW

- ***Decrease of fuel pins and fuel subassemblies consumption rate, respectively, by factor of ~3 and ~6*** by increasing dimensions of fuel pins and SA because of lower power density
- Simplification of refueling system. For this purpose, large-capacity in-vessel storage is provided
- Use of relatively low-cost, however, quite effective in-vessel shielding

Zero SVRE concept and optimization of technical and economical characteristics

Current status

- In 2008 the new Rules of Nuclear Safety (NP-082-070) were issued in Russia. In these Rules, there is no strict requirement of assurance of negative reactivity coefficient related to specific volume of coolant. Therefore, core designs with positive SVRE value can be considered
- Studies are carried out on SVRE effect on the core self-protection characteristics under ULOF conditions in order to estimate permissible SVRE value
- The role of passive control rods in such accident is still a debating point
- Authors tried to understand: 1) What are potential advantages of the core with relatively low positive SVRE value? and 2) Are there any motivations for abandonment of "zero SVRE" concept?

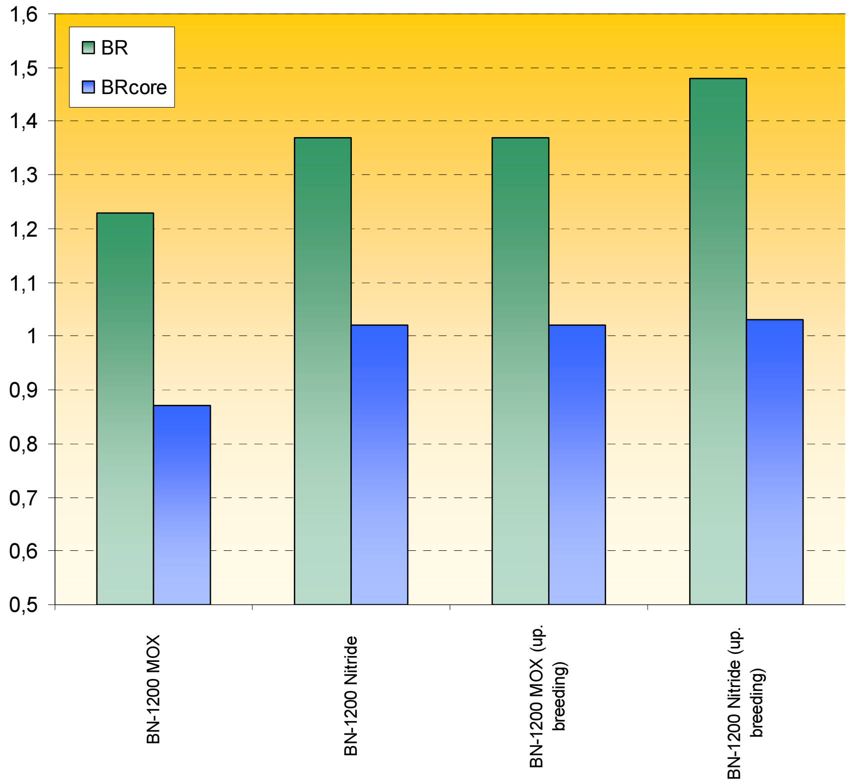
The following potential improvements of core parameters with "non-zero" SVRE value:

- better H/D ratio because of core height increase up to 100 cm and SA number decrease down to 390,
- use of the upper axial blanket
- increase of fuel volume fraction from 0.47 to 0.51 and fuel pin diameter up to 10.5 mm, and

make it possible to:

- increase control rods worth and abandon the use of expensive enriched boron carbide
- increase BR from ~1.2 to ~1.4, i.e. to approximately double (BR – 1) value
- may be reach CBR~1 with MOX fuel
- assure zero excess reactivity in MOX fuel core with reactor on power

Fuel cycle requirements: fuel breeding



✓ ***This core design provides the possibility of BR varying within the range from ~1.2 to ~1.45*** by the following measures:

- ❑ Increase of fuel volume fraction
- ❑ Increase of MOX fuel density
- ❑ Use of high-density mixed nitride fuel (the possibility of use of metal fuel is also studied)
- ❑ Use of radial and lower axial blanket
- ❑ Use of the upper axial blanket provided that reactor safety with non-zero SVRE is proved

✓ ***BR values in reference core design:***

- ***~1.19 - for MOX fuel***
- ***~1.33 – for nitride fuel***

Requirements of fuel cycle: fuel consumption balance

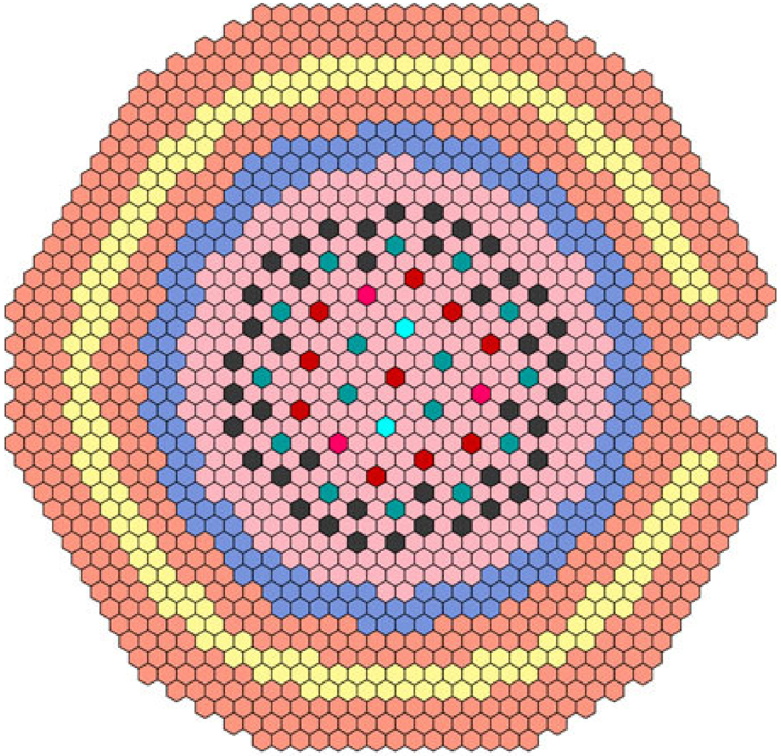
Reactor Power (thermal /electric), MW	BN-1200 2900 / 1200	
Fuel	oxide	nitride
Fuel life-time, year / Refueling ratio	5 / 5	4 / 4
Average fuel burn-up, % h.a.	11.6	6.7
Pu start loading, t	6.3	6.5
Annual Pu consumption, t. h.a.	1.2	1.6
External fuel cycle, year	3	3
Total Pu consumption including BN-800 start loading and filling fuel cycle, t/GW	9.9	11.3

✓ ***Is increased Pu loading of BN-1200 a drawback from the point of view of fuel balance?***

Pu consumption for start loading of one BN-1200 is the same as for BN-800 reactor (increased start loading is compensated by decreased annual Pu consumption)

- ***BN-1200 fuel cycle concept*** suggests a start-up of reactor using reactor-grade Pu from thermal reactors with gradual transition to use of own regenerated fuel.
- Small series of BN-1200 reactors with capacity of 10-15 GW will allow to utilize reactor-grade Pu stock to be accumulated in Russia by 2030-2035, i.e. will facilitate solution SNF problem of thermal reactors.
- Neutron-physical characteristics of the core changes weakly at the expense of non-uniformity of accumulated Pu nuclide composition and fuel isotope composition change during recycle, when using the method on Pu mass fraction correction by its isotope composition.

Requirements of fuel cycle: MA management (1)



Total rests of MA for different ways of their utilization

Way of MA utilization	Pu recycle only	homogeneous			heterogeneous		
		All MA	Am+Np	Np	All MA	Am+Np	Np
The rest of MA	2520	310	500	1150	315	500	1140

- When developing concept for MA management in BN-1200, the following scenarios were considered :
  - only Pu recycle, disposal of MA in repositories
  - homogeneous MA transmutation in fuel
  - heterogeneous transmutation of MA in 42 special core SA (heterogeneous transmutation of MA in 78 SA of radial blanket was considered, but it has been recognized as inefficient as yet)
- The following additional options were considered for transmutation scenarios above:
  - recycle of all MA;
  - recycle of MA without Cm;
  - recycle of Np only.
- Preliminary calculation results:
  - ✓ ***It would be utilized more than 2 tones of MA during BN-1200 life-time***
  - ✓ ***The amount of MA could be decreased by an order***

Requirements of fuel cycle: MA management (2)

Heat generation in regenerated fuel, kW/SA

Fuel cycle option	№ of fuel life-time		
	1	2	8
Pu recycle (without MA)	0.30	0.20	0.10
All MA recycle (Np, Am and Cm)	0.56	0.95	0.66
Np and Am recycle	0.44	0.61	0.26
Np recycle	0.29	0.37	0.13
All MA recycle (heterogeneous)	2.66	4.42	4.37
Np and Am recycle (heterogeneous)	1.53	1.30	0.60
Np recycle (heterogeneous)	0.22	0.33	0.13

γ-radiation source intensity in regenerated fuel, 10^{13}/s SA

Fuel cycle option	№ of fuel life-time		
	1	2	8
Pu recycle (without MA)	3.80	2.45	1.17
All MA recycle (Np, Am and Cm)	23.4	25.9	14.2
Np and Am recycle	21.9	20.7	8.99
Np recycle	3.77	4.67	1.60
All MA recycle (heterogeneous)	184	185	108
Np and Am recycle (heterogeneous)	171	138	59.8
Np recycle (heterogeneous)	2.89	4.09	1.51

Neutron radiation source intensity in regenerated fuel, 10^{6}/s SA

Fuel cycle option	№ of fuel life-time		
	1	2	8
Pu recycle (without MA)	13.7	11.3	0.785
All MA recycle (Np, Am and Cm)	476	1030	1550
Np and Am recycle	16.9	22.6	13.0
Np recycle	13.6	16.2	9.41
All MA recycle (heterogeneous)	4300	9140	14300
Np and Am recycle (heterogeneous)	39.9	38.2	21.0
Np recycle (heterogeneous)	10.2	14.1	9.00

"Payment" for MA utilization is an essential worsening of radiation properties of regenerated fuel:

Homogeneous MA transmutation:

- *heat generation increases ~7 times,*
- *γ-radiation ~10 times,*
- *neutron-radiation ~600 times*

Heterogeneous MA transmutation :

- *heat generation increases ~40 times,*
- *γ-radiation ~100 times,*
- *neutron-radiation ~2000 times*

Heterogeneous transmutation of MA without Cm is the best compromise, which doesn't decrease efficiency of transmutation due to own radioactive decay, but decreases:

- *heat generation ~7 times,*
- *neutron-radiation ~ 500 times.*

In BN-1200 concept the transmutation is considered as additional function, which shouldn't be paid at the expense of electricity cost, but it should be paid at the expense of funds for radioactive waste management. Optimal option of MA transmutation will be defined on the basis of feasibility study.

Conclusion

Concept of BN-1200 core using MOX or nitride fuel provides:

✓ ***Improving technical and economic indices of BN reactor:***

- Essential decrease of expenses for fuel at the expense of increasing fuel burn-up and optimization of fuel pin and subassembly design
- Transition to one-year cycle (interval between reloadings), increase of load factor up to the value not less than 0.9
- Decrease of capital outlay at the expense of simplification of radiation shielding and fuel reloading system

✓ ***Enhancing safety:***

- Use of inherent safety properties: low excess reactivity and minimal Sodium Void Reactivity Effect
- Power distribution field stability
- Development of safety system on passive principles

✓ ***Solving problems of fuel cycle:***

- Efficient breeding of fuel (BR from 1.2 till 1.45)
- Providing full utilization of VVER SNF in small series of BN-reactors
- Full utilization of long-lived MA of VVER and BN- reactors (not less than 2 tons of MA)