Studies on influence of sodium void reactivity effect on the concept of the core and safety of advanced fast reactor

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Introduction

NEW requirement after Chernobyl accident

– zero integral sodium void reactivity effect (SVRE)

A few possible concepts were proposed in order to meet this new requirement: –

1) **arrangement of sodium plenum above the core**
2) **decrease of core height**
3) **annular or modular core**
4) **adding moderator to the reactor and etc.**

Concept 1 was adopted - *for the BN-800 reactor design*

Combined concept (1+2) is proposed - *for BN-1200 type reactor*

Main advantage – improved safety feature *(in the case of severe accident voiding of sodium plenum due sodium boiling leads to introduction of negative reactivity)*

Main disadvantage – deterioration of technical and economical characteristics *(decrease of breeding ratio, significant increase of dimensions of the core diagrid and rotating plug, decrease of control rods worth etc.)*

The paper is devoted to studies on influence of sodium void reactivity effect (SVRE) on safety and technical and economical characteristics of BN-1200 type reactor.

Procedure of complex analysis

Three following options of core designs were chosen for comparative safety analysis of BN-1200 type reactor:

1) **Core with sodium plenum designed in the stage of technical proposal *(flattened core with sodium plenum - reference option)***
2) **Core with upper axial fertile blanket *(Traditional design)***
3) **Core of increased height (100cm refer to 85cm) and with sodium plenum *(Combined option)***

Comparative analysis includes in itself the following steps:

- **Analytical analysis of neutronic characteristics *(Reactivity effects, power distribution in the core and etc.)***
- **Reactor safety analysis for three core designs and under selected set of accidents affected by SVRE.**
- **Evaluation of the effect of adopted core characteristics and results of safety analysis on technical and economical parameters of the reactor plant.**
- **Option of most favourable core design within the framework of specified scope of the analysis**

Reactor safety analysis for three core designs(1)

List of beyond design bases accidents (BDBA)
studied within the framework of reactor safety analysis

Comparison of safety characteristics of reactor with three core designs was made for the following list of BDBAs:

1) **Full loss of grid and independent power supply of NPP with simultaneous failure of reactor safety system (ULOF accident).**
2) **Loss of grid power supply of NPP with simultaneous failure of reactor safety system.**
3) **Loss of feed water supply to the steam generators with simultaneous failure of reactor safety system.**
4) **De-energizing of some primary pumps with simultaneous failure of control system of the pumps remaining in operation that caused gas entrainment by the sodium flow.**

The ULOF accident would result in the most drastic consequences.

In accidents 2, 3 and 4 significant temperature rises are possible in the core resulting in sodium boiling onset in the hottest channels.

Reactor safety analysis (2)

Input data

Table 1. Main technical characteristics of the reactor plant

1	Reactor thermal power, MW	2800
2	Range of power control, % N_o	25-100
3	Reactor refueling interval, eff. days	330
4	Parameters of the primary circuit: sodium temperature at the core inlet, °C sodium temperature at the IHX inlet, °C sodium flow rate in IHX, kg/s primary sodium pump pressure head, mlc	 410 550 15784 58
5	Parameters of the secondary circuit: sodium temperature at the SG inlet, °C sodium temperature at the SG outlet, °C sodium flow rate in one loop, kg/s secondary sodium pump pressure head, mlc	 527 355 3193 47
6	Number of primary and secondary loops	4

Comment: The same reactor parameters were chosen for all considered cases

Reactor safety analysis (3)

Input data

Table 2. Main characteristics of core designs under study the reactor plant

	Reference	Parametric cases	
	CASE 1	CASE 2	CASE 3
Core height, cm	85	85	100
Upper blanket	Sodium plenum	Fertile blanket	Sodium plenum
Number of SAs	432	432	366
Fuel enrichment, %.	17.96	17.62	17.11
Max fuel burn-up, % h.a	16.44	16.38	18.51
Average fuel burn-up in spent SA, % h.a.	10.76	10.56	10.79
SVRE, % ΔK/K	+0,5	+1.9	+1.31
Excess reactivity for the fuel burn-up, % ΔK/K	1.5	1.3	1.29
BR	1.25	1.34	1.25
Core BR	0.88	0.88	0.93
Pu inventory, kg	7531	7390	7168
Max power density, W/cm3	378	374	425
Max linear power, kW/m	41.9	41.4	47.1
Max SA power, MW	8.24	8.42	10.64

Comments:

- ✓ Number of Sas is decreased for case 3
- ✓ SRVE is minimal for case 1
- ✓ Additional excess of reactivity for burn-up is necessary for case 1
- ✓ Breeding ratio is the same for cases 1 and 3
- ✓ Power density is higher for case 3

Reactor safety analysis (4)

Reactivity effects and coefficients

Table 3. Components of power reactivity coefficient, 1/MWe

Case	1	2	3
Doppler effect (523-6830 K)	-5.36×10^{-6}	-4.62×10^{-6}	-5.46×10^{-6}
Axial expansion (on steel cladding)	-7.0×10^{-8}	-6.8×10^{-8}	-7.5×10^{-8}
Radial expansion	-4.2×10^{-7}	-4.2×10^{-7}	-3.8×10^{-7}
Sodium density component	6.4×10^{-8}	2.6×10^{-7}	1.5×10^{-7}
Net effect	-5.8×10^{-6}	-4.9×10^{-6}	-5.8×10^{-6}

Comment to Table: Only sodium density component is positive and it is true for all cases.

As for temperature reactivity coefficient 1/°C Doppler effect and sodium density component are positive but nevertheless Net effect is negative.

Reactor safety analysis (5)

Reactivity effects and coefficients

Table 4. SVRE caused by sodium removal from local sub-areas of core

	Drying-out areas	1st 1/3 radial section of the core	2nd 1/3 radial section of the core	3rd 1/3 radial section of the core	All SAs of the core
1	BA + SP+1/3 section of the core height	-0.00452 0.00167 -0.00247	-0.00360 0.00128 -0.00197	-0.00232 -0.00004 -0.00156	- - -
2	BA + SP+2/3 section of the core height	0.00021 0.00702 0.00425	0.00018 0.00519 0.00114	-0.00156 0.00075 -0.00053	-0.00007 0.01262 0.00571
3	BA + SP + whole core height	0.00434 0.01102 0.00930	0.00278 0.00760 0.00308	-0.00212 0.00104 -0.00005	0.005 0.01877 0.01310

Comment:

✓ Integral SVRE is positive for all cases but for reference option it is minimal.

✓ For cases 1 and 3 voiding of upper core part gives negative effect.

Case 1 (Hcore=85, with Na plenum)

Case 2 (Hcore=85, with upper axial fertile blanket)

Case 3 (Hcore=100, with Na plenum)

Reactor safety analysis (6)

ULOF accident

COREMELT **code was used for ULOF study**

CODE PURPOSE **is analytical studies on BDBA in the reactor accompanied by**

- **sodium boiling**
- **fuel and steel melt-down**
- **molten fuel and steel relocation and refreezing in the core**

CODE MODEL

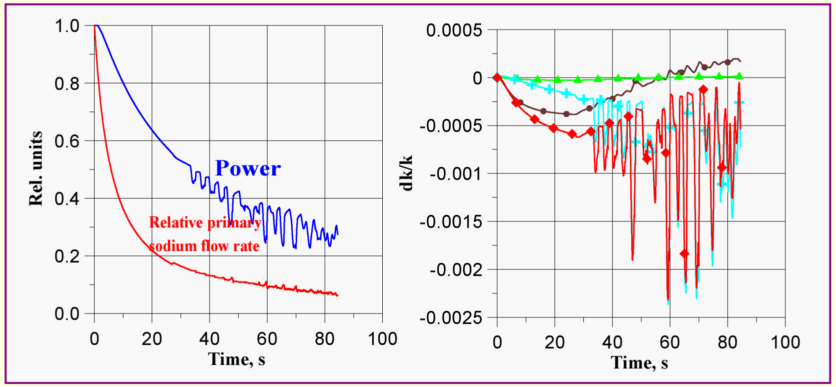
- **2D multi-component, multi-speed thermally non- equilibrium thermal hydraulic model, based on "Porous body" approach**
- **"Point kinetics"**

CODE's 2D CALCULATIVE DOMAIN **covers whole reactor including most important components of the primary circuit (such as core, upper plenum, heat exchangers, pumps and so on)**

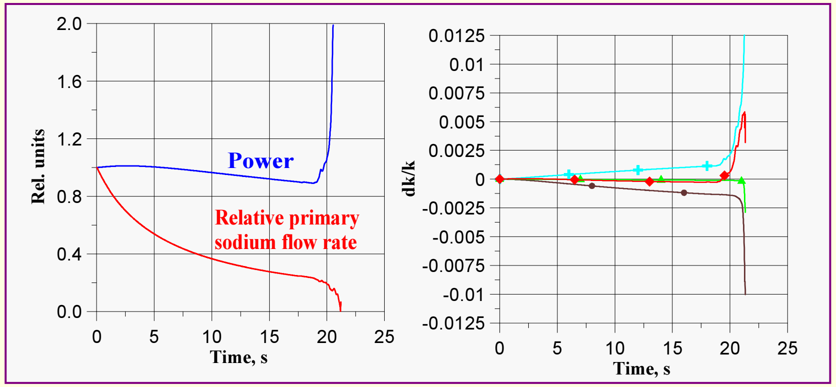
Reactor safety analysis (7)

ULOF accident

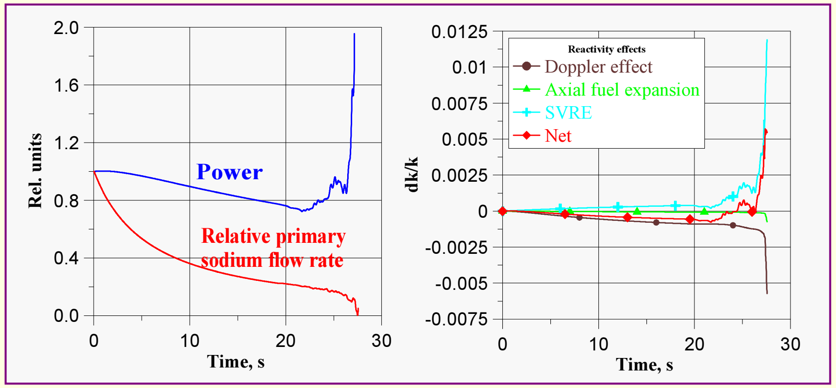
Case 1



Case 2



Case 3



Behavior of reactor parameters. ULOF accident

Comments:

- **Case 1** - Power gradually decreases due to negative Net reactivity, core is heating up and after half a minute sodium boiling starts in the core, voiding of upper core part gives additional negative contribution in Net reactivity and power continue to go down. **Reactor self-protection is provided**

- **Case 2 and 3** - sodium boiling results in positive contribution to Net reactivity, reactor runaway occurs leading to the core disruption after 20-28 seconds. **Avalability of sodium plenum in case 3 can't prevent power excursion**

Reactor safety analysis (8)

BDBA – 2,3,4

DINROS code was used for study BDBA-2,3,4

CODE PURPOSE: DINROS is typycal system code intended for comprehensive analysis of transient and accident processes occurring in three-circuit multi-loop reactor plants with detailed modeling of reactor design.

CODE MODEL

- **1D 1-phase thermal hydraulic models for primary and secondary loops**
- **reactor control and safety systems and reactivity feedbacks are carefully modeled**
- **thermal-mechanical pin model is available**
- **taking into account spatial changes of the core power field caused by movement of absorber rods are taking into account**
- **“Point kinetics”**

Reactor safety analysis (8)

BDBA – 2,3,4

BDBA 2 - Development of BDBA caused by the loss of grid power supply with simultaneous failure of reactor safety system is almost the same for all core design options. Neither sodium boiling occurs in the entire core, nor rapid core disruption. However sodium boiling onset is possible in some of the hottest fuel subassemblies of the core. The extent of boiling is min in the reference CASE 1 and it is max in CASE 2 (no sodium plenum)

BDBA 3 - Accident with the loss of feed water supply to all steam generators leads to neither sodium boiling onset in the reactor nor rapid meltdown (disruption) of the core irrespective of core design. In this respect, all three core designs assure self-protection of the reactor under conditions of this BDBA. However, steady state reactor temperatures reached in the course of accident are different for three core designs. Min sodium temperature at the reactor outlet is obtained in the reference CASE 1. This is about 730^{o}C. In CASE 2 and 3 this temperature is 50°C higher (780^{o}C). This difference is significant, if it is considered from the standpoint of keeping reactor vessel integrity

Evaluation of influence on economical parameters

Symplified methodology of evaluation:

Deviation of specific energy cost:

$$\delta C_j = \sum_k \delta C^d_{j,k} + \sum_S \sum_k \delta C^p_{j,k,s} \cdot \lambda_{j,s}$$

j **– number of considered option**

k **– index of energy cost component (*c* – capital cost, *f* – fuel cost, *o* – operating cost)**

Upper indices *d* and *p* correspond to the deviations of deterministic and probabilistic energy cost component.

Probabilistic component has additional index S corresponding to the accident or abnormal operating conditions occurred with probability $\lambda_{j,s}$ Since in the above cases $\lambda_{j,s}$ values are too small (corresponding to 10^{-8} - 10^{-10} 1/year intensity), then:

$\delta C^d_j >> \delta C^p_j$, **and the proper contributions to the total costs can be neglected.**

It can be assumed for approximate estimation that the fuel fraction of NPP energy cost is 30-35% ,and that one half of this fraction is determined by the cost of fuel reprocessing, and the other half relates to the fuel element and SA fabrication cost.

In this view, energy cost would decrease in option 2 by 1.0-1.4%,
and in option 3 by 3-3.5%

and case 3 becomess more preferable.

In addition to the decrease of the fuel component of energy cost, capital cost would be also reduced because of the decrease of the core dimensions owing to the possibility of decreasing diameter of the core diagrid and reactor vessel

Finaly it means that from economical standpoint most preferable case is Case 3

Evaluation of influence on safety parameters

***Table 5.** Comparison of safety characteristics*

Safety factors	Positive factors			Negative factors		
	Design option			Design option		
	1	2	3	1	2	
Possibility of assurance of reactor self-protection under conditions of ULOF accident	-			-	▼	▼
Reactor temperature increase in case of BDBA caused by loss of feed water supply to SG	-			-	▲	▲
Reactor temperature increase in case of BDBA caused by loss of grid power supply of NPP	-			-	▲	▲
Risk of core damage caused by gas entrainment by sodium flow in the main primary pumps	-			-	▲▲	▲

Comments: Deviation from reference case leads to deterioration of safety parameters

- Self-protection property disapear;
- For BDBA 2 and 3 temperature increases and probability to damage fuel pins, reactor vessel and atc. are raised up.
- For BDBA 4 the more is SVRE the more is the risk of core damage due to reactIvity insertion coused by gas injection in the core

Evaluation of influence on economical parameters

Table 6. ***Comparison of economical characteristics***

Technical and economical characteristics	Positive factors			Negative factors		
	Design option			Design option		
	1	2	3	1	2	3
Number of SAs, diameters of core, core diagrid and rotating plug	-	-	▼	-	-	
Reactor breeding ratio	-	▲	-	-		-
Excess reactivity for the fuel burn-up	-	▼	▼	-		
Fuel inventory in the core	-	▼	▼▼	-		
Specific energy cost	-	▼	▼▼	-		

Comments: It is confirmed that considered design variations provide an improvement of economical characteristics

Conclusion

- **Reference option 1 has advantages of two other options from the standpoint of reactor safety. It assures reactor self-protection (in contrast to the other options) under conditions of ULOF BDBA. This option is also characterized by less temperature rise under conditions of other considered BDBAs. Unless potential losses that may emerge in case of NPP accident are taken into account, reference option loses out to case 2 and 3 in energy cost value**

- **Case 3 *(core height increased up to 100 cm)* is most preferable from economical standpoint. Its advantages are caused by**
  - **reduction of the number of fuel SA in the core,**
  - **decrease of fuel inventory**
  - **decrease of excess reactivity for the fuel burn-up**

- **Case 2 *(with the upper fertile blanket)* has an advantage of reference option from the standpoint of breeding ratio and this point may become of crucial importance under certain conditions**

- **It is difficult to make quantitative estimates of potential losses caused by the accidents, however it is obvious that more or less severe accident in any NPP would cause a chain of considerable economical losses in the whole nuclear energy industry. Therefore final preference is given to designs assuring self-protection of the reactor in spite its additional costs and even under conditions of incredible BDBA .**