CASCADE SUBCRITICAL MOLTEN SALT REACTOR (CSMSR) MAIN FEATURES AND RESTRICTIONS

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Actuality

- There is no definite strategy for incineration of long-lived radioactive waste, especially minor actinides (MA).
- Effective minor actinides incineration can be performed safely in ADS because of small value of delayed neutron yield β_{eff}.
- Such burner must have high efficiency (high unit power) and adjustment to the nuclear fuel cycle.

TASK

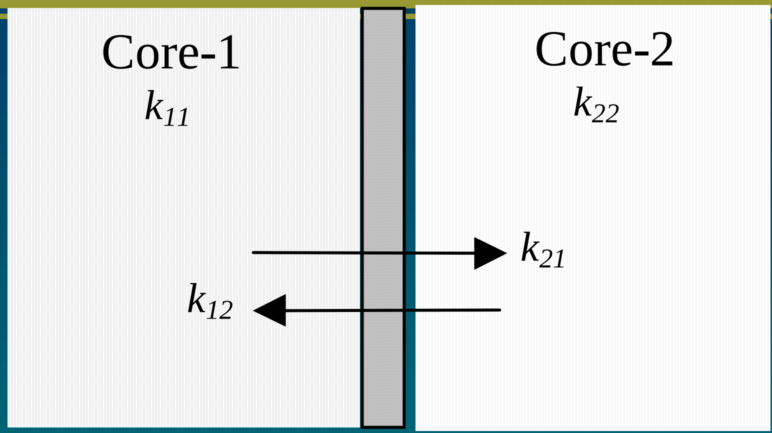
THE POWER OF PROTON ACCELERATOR-DRIVER W_A AND REACTOR WITH SUBCRITICALITY ΔK ARE RELATED AS

$W_A \sim 0.6 \Delta K^* W_R$ i.e. $W_A \sim 30$ MW at $W_R = 1$ GWth

To reduce W_A we used the cascade scheme of neutron flux amplification wnich is based on the idea of two-cores reactor with unilateral thermal neutron flux.

Our task is to investigate the possibilities of reactor- burner based on subcritical cascade scheme

Cascade scheme of neutron flux amplification



The cascade scheme of neutron flux amplification.

At $\Delta k_1 \approx \Delta k_2$ and $k_{12} << \Delta k << 1$ Cascade amplification factor $A \approx 1 + \dfrac{k_{21}}{\Delta k}$, and at the fixed blanket power W_b the necessary accelerator power can be reduced in A times: $W_a \to W_a/A$. At $k_{12} = 0.2 \div 0.4$ $A = 5 \div 10$. The experimental and theoretical justification of the cascade principle was performed in the framework of the ISTC Project #1486 .

Initial assumptions and requirements

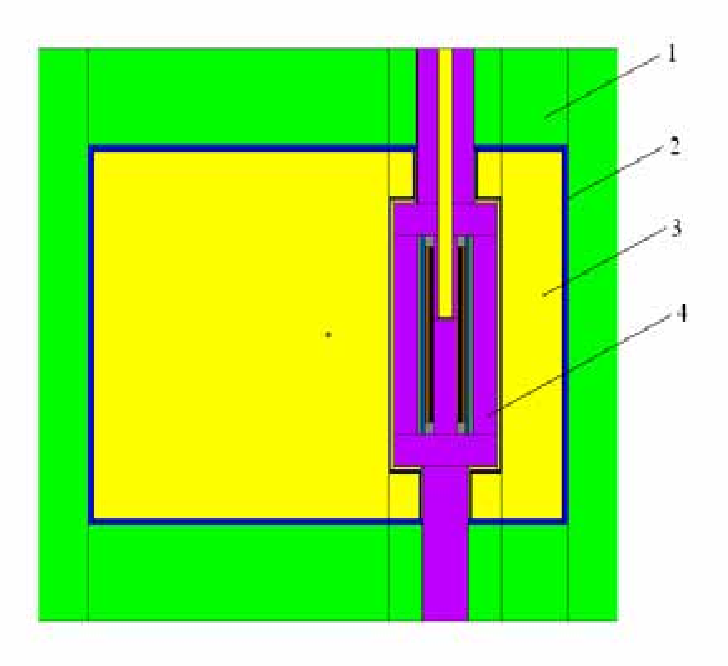
- Two section cascade subcritical reactor, with zone of cascade amplification (ZCA) and transmutation zone (TZ).
- Subcriticality margin $\Delta K_{eff}=0.05$
- 1 GeV proton accelerator driver with 10 mA current
- Homogeneuos TZ with NaF-ZrF_4 molten salt

Scope of investigation

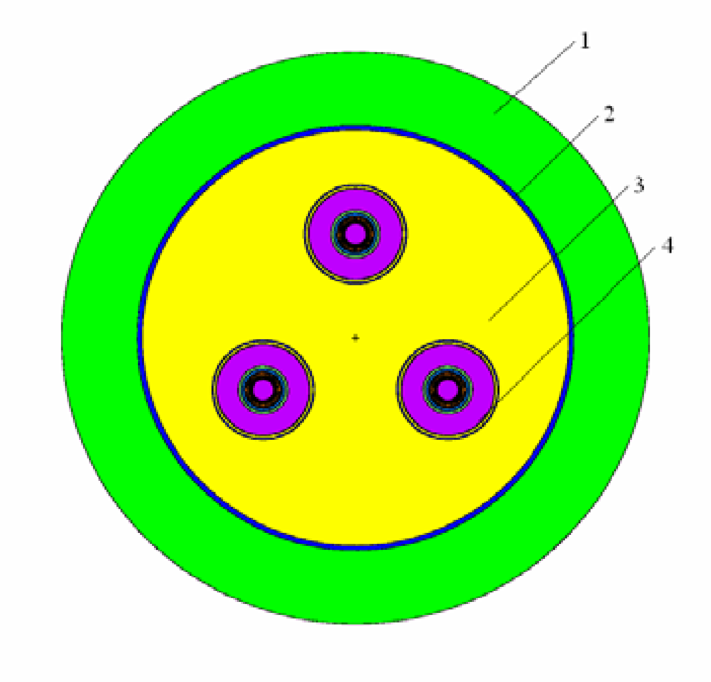
- Our investigation was aimed to study principal aspects concerning cascade subcritical molten salt reactor, including:
- a) proton beam conversion to neutron source;
- b) main neutron-physics properties of the reactor;
- c) thermo-hydraulics calculations of ZCA;
  d) peculiarity of the reactor safety;
  e) choice of molten salt; etc.
- In this report we focused on neutron-physics problems paying less attention to other ones

Reactor composition

3 main elements of the reactor-burner are proton accelerator driver, ZCA and TZ (fig.1).



a) vertical section



b) horizontal section

Fig. 1. CSMSR structure. 1 - reflector; 2 - TZ hull; 3 -TZ; 4 - ZCA

ZCA structure

Structure of ZCA is the critical point for efficiency of the whole reactor. We applied following method for elaboration of ZCA which based on heterogeneous scheme with fuel rods (fig. 2):

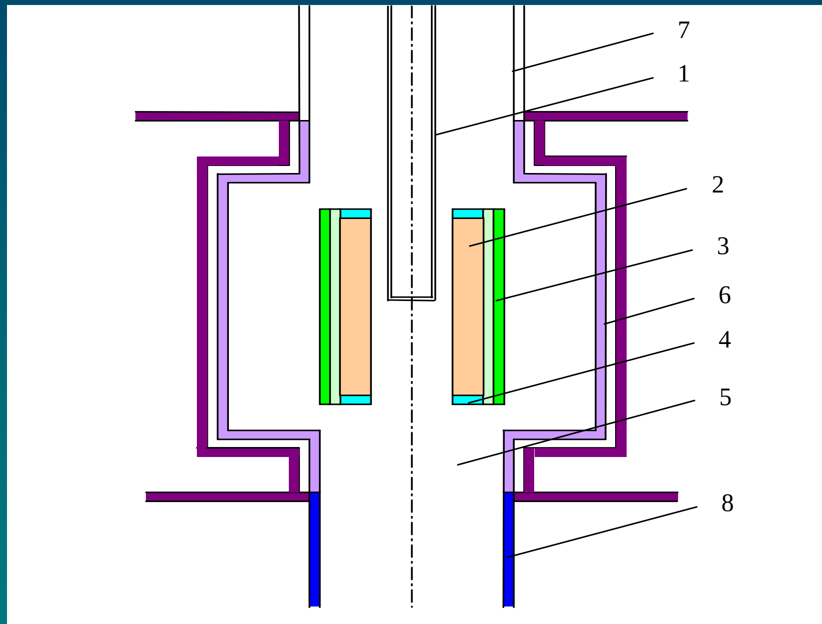


Fig. 2. ZCA structure: 1 – proton guide tube; 2 – Pu zone; 3 – Np zone; 4 – Pu fuel rods ending with Np; 5 - Pb-Bi eutectic; 6 – ZCA cladding; 7,8 – outlet and inlet tube for Pb-Bi eutectic

ZCA has a similar structure both in radial and axial directions.

ZCA structure (cont.)

This scheme provides the fast spectrum of neutrons. Prototype for fuel rods region is similar to Russian project BREST.

This structure increases CAF but in the other hand implies some problem of ZCA (Fig. 3).

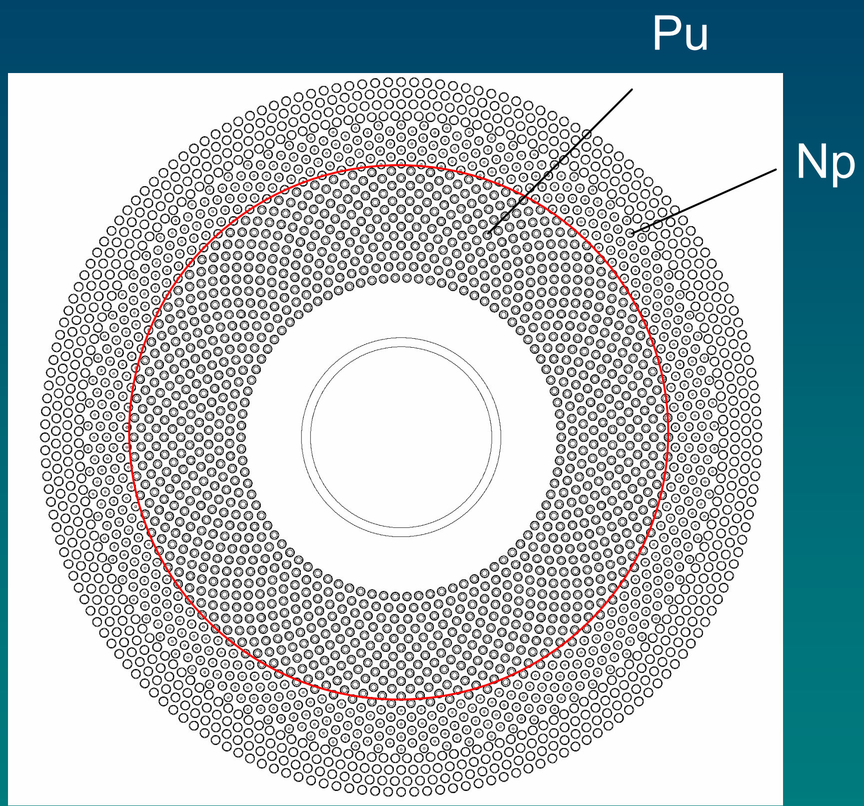


Fig 3. Structure of ZCA fuel rods

ZCA structure (cont.)

ZCA is filled by the eutectic Pb-Bi and has two-layer structure; inner - Pu rods with K_{IN} = 2.4 and outer - ^{237}Np rods.
Pb-BI eutectic is used simultaneously as the neutron production target, coolant and neutron deceleration media between ZT and ZCA. Radius of ZCA is 37 cm.

Power release in ZCA.
Increasing CAF requires high specific power q_v. To satisfy this requirement we keep main thermo-hydraulics parameters at the maximal permissible level with $q_{v\sim}$470 kW/litre. This value is about 2.5 higher than q_v value in BREST used as prototype.
We choose three ZCA to reduce the load to windows between accelerator and reactor and to decrease power distribution peak factor at TZ.

Transmutation zone.

- We taken homogeneous composition, that favors actinides fission and allows to avoid the problems with graphite moderator in core.
- Graphite reflector minimizes the neutron losses and makes smooth power distribution.
- NaF-ZrF_4 is chosen as salt composition what has preference compared to lithium-beryllium salt both in handling and actinides solubility.
- Zone composition forms intermediate spectrum of neutrons.

When optimizing we fit configuration of TZ and salt composition, including ratio between Pu and MA components.
As the result, we have obtained
TZ 230 cm height and 170 cm radius.
These dimensions allow to prevent the significant ZCA interference.

Transmutation zone. Fuel.

- For feeding of TZ we use spent fuel of VVER. Its composition is similar to PWR spent fuel.
- High values of heavy nuclides (HN) contents and MA/Pu ratio improve reactor capacity as MA burner. But these parameters are restricted by solubility limits and, in the case of MA/Pu ratio, requirement of the sufficient reactivity.

Transmutation zone. Fuel (cont.)

- To increase burnup of MA , we rise its fraction in the start TZ fuel from 16% as in irradiated VVER fuel up to 25%.

  At the beginning of operation the salt contains

  3.9 mol % heavy nuclides.

- For feeding composition along the operation period we considered :

1) VVER spent fuel and

2) composition with two times MA fraction increased.

Neuron-Physics Characteristics

We used two codes based on Monte-Carlo method:

1) Russian MCU code.
2) MCNP code coupled with burnup module ORIGEN. This complex was created within cooperation of RRC KI and FZR.

The main neutrons-physics characteristics are the following:

- Primary neutron source produces 19-22 fissions in core, total reactor power is 800 MWth, with ZCA/TZ fission relation 19:81.
- CAF is equal 3.
- ZCA and TZ power distribution are satisfactory.
- TZ reactivity effects are favourable also. Only freezing of salt has positive reactivity effect, but even in this case the reactor is still subcritical with $\Delta K_{eff}=0.026$.
- Operation time between ZCA reloading is 0.8 year with 9% fuel burnup. ZCA fuel burnup doesn't imply a serious problem and can be compensated.

Safety issues

- Being subcritical reactor with margin ΔKeff=0.05 CSMSR has significant advantages of critical reactors in safety issues. But subcritical condition entails strict undesirable limitation on reactor power level. So, taking into account CSMSR reactivity properties we would suppose reasonable choice ΔKeff in question. For decreasing this margin it is necessary to correct nuclear data for MA.
- Subcritical condition, using proton accelerator for power drive and stability of power distribution in CSMSR allow to eliminate CPS, including moving absorber rods.
- As a reactor with one-way bond between two zones, CSMSR requires specific organization of reactivity control. At the moment we are elaborating reactivity control system for our production reactors, and we are going to use our experience for CSMSR.

Efficiency of MA incineration

Efficiency calculations were carried out on the basis of the neutronics calculation results (table 1).

Table 1. Initial data for calculation

Parameter	Value
Core volume	17.88 m^3
Primary circuit volume	21.83 m^3
TZ power	645.6 MWth
Average overall circuit power density	29.6 Wth/cm^3
Neutron flux	$5 \cdot 10^{14}$ $n/(cm^2 s)$
Actinide losses during reprocessing	0.1%
Core reprocessing period	1200 days
Annual load	300 days

Power density and neutron flux are rather far from desirable values.

Efficiency of MA incineration (cont.)

We calculated incineration capacity averaged along 50 years operation period for 2 options of feed composition. The table 2 presents our results in comparison with incineration characteristics of homogenous critical burner SPHINX in equilibrium.

Table 2. Incineration characteristics CSMSR compared to SPHINX.

Parameter	CSMSR		SPHINX
	VVER spend fuel	VVER spend fuel with increased MA fraction	
Molar concentration of actinides in salt*, %	6	7	0.75
Mass of actinides in primary circuit*, kg	9851	11868	3600
Specific mass of actinides in primary circuit*, kg/MWth	12.3	14.8	3.0
Actinides composition U/Np/Pu/Am/Cu*, %	1.7/2.1/83.3/9.5/3.4	2.1/2.1/79.6/13.0/3.3	0.4/1.5/72.5/7.5/18
Incineration capacity HM/MA/Np**, kg/year	193.7/26/20	193.7/51/19.3	~365/25.7/16
Specific incineration capacity HM/MA/Np **, kg/TWhth	33.6/4.5/3.5	33.6/8.9/3.4	~42/2.9/1.8

Comment: * - end of CSMSR operation, ** - evaluations for SPHINX under the data presented in MOST report

CSMSR requires a large specific fuel loading. Concerning incineration characteristics CSMSR compared with SPHINX (thermal power is 1215MW) has advantages for MA incineration. With 30 years cooling period VVER annually produces 32.4 kg MA and 15.2 kg Np. Thus, concerning MA incineration CSMSR can support up to 1.6 VVER.

Conclusions

- Cascade scheme can reduce ~3 times the power of accelerator-driver at fixed blanket power.
- CSMSR-burner with W_A =10 MW, W_R =800 MWth and subcriticality ΔKeff=0.05 can incinerate ~50 kg of MA per year, i.e. MA produced by 5 thermal reactor of the same power.
- Restriction ΔKeff=0.05 should be analyzed more carefully using the new MA nuclear data.
- Disadvantage of CSMSR is the intermediate neutron spectrum in TZ and as consequence the high ratio Pu/MA ~ 4/1.
- To enchance the efficiency of ADS-burner it is necessary to enlarge the cascade amplification factor and to reduce Pu/MA ratio.