NEUTRONIC ASPECTS OF NUCLEAR BURNING WAVE MODULAR FAST REACTOR CONCEPT SUBSTANTIATION

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Abstract - The report presents the results of analytical studies aimed at substantiation of the concept of a nuclear burning wave fast reactor, including a high-temperature helium reactor with a pebble-bed core, allowable to provide long-term reactor operation with virtually constant power distribution. The first part of the report deals with an immovable fuel. Nevertheless, if burnup should be limited by its allowable value, it is expedient to consider the core with a movable fuel. This analysis is given in the second part of the report, which considers the core option with a pebble-bed core, which could be unloaded after having achieved the prescribed burnup value.

As a result of the studies, the conditions were determined to maintain the operation mode of the reactor with the fast core, in which replacement of enriched uranium by natural one and its long-term burnout are possible. These conditions are the following:

- to accumulate the critical $^{239}\text{Pu}$ concentration a dense fuel should be used in the blanket. Metallic uranium or a composition of plutonium-doped natural uranium is most appropriate for this purpose. Numerous recent studies of substantiation of application of zirconium- and plutonium-doped metallic uranium in reactors offer additional possibilities for implementation of the wave mode of power release;
- to provide plutonium accumulation in a reasonable time the specific reactor power should be 200-300 MW/m$^3$;
- in the reactor with a movable pebble bed, distribution of the critical $^{239}\text{Pu}$ concentration over the core height should be uniform, otherwise, a nuclear burning wave, owing to which the burning mode is kept, attenuates fast. For this purpose, the reactor with a circulating fuel needs in an operation period, within which the critical $^{239}\text{Pu}$ concentration is distributed uniformly. From this moment the initial spent fuel is possible to be replaced by natural or doped uranium.

I. INTRODUCTION

In [1], theoretical prerequisites are provided for fast reactor concept substantiation. The fast reactor is developed in order to solve the problem of fuel supplies by highly extensive use of natural uranium, implementation of the highest characteristics for breeding new fissile materials from fertile isotopes and use of, in the same reactor, the built-up fissile isotopes independently of the spent nuclear fuel (SNF) reprocessing rate in the external fuel cycle, use of natural uranium for the makeup fuel, which creates the most favorable conditions for maintaining the non-proliferation mode considering the fact that there is no SNF reprocessing.

In order to implement such reactor concept, two main conditions are to be satisfied. The first neutronic condition is that plutonium built up during burnup is sufficient to ensure the reactor critical condition at an average for the cycle. The second process condition is that fuel burnup needed for ensuring the reactor critical condition can be achieved by process means, i.e. fuel rods will be able to operate.

In order to substantiate neutronic conditions for implementation of the proposed open cycle fast reactor concept, analytical studies were performed with the main results presented here. The first analysis portion deals with a fixed fuel core. But if it is required to limit the burnup by the value that is allowed and that can be achieved using the existing technology, it is expedient to consider a moving fuel core. This analysis is considered in the second report part, which deals with the core made of spherical
fuel elements that can be unloaded at achievement of the assigned burnup.

II. RESULTS OF THE FIXED FUEL COMPOSITION REACTOR ANALYSIS

The reactor model and burning process are given in Figure 1.

![Diagram of reactor model and burning process](image)

Fig. 1: Seed zone reactor core model and burning process:
(a) core model, (b) burning process.

References [2, 3] show that for the ~2000 MW reactor of the same composition as BN-600, of which the seed zone has the radius of 103 cm and length of 90 cm, the fission wave speed is approximately 10 cm/year. Hence, when the reactor core is 550 cm long, the cycle duration is approximately 50 years. The fuel burnup reaches 200–240 MW·day/kg. Note that results slightly depend on the coolant type (sodium or helium) and on seed zone initial length selection. Calculations were performed in the multi-group energy approximation using the WIMS-D/4 [4] and MCU [5] codes. In WIMS-D/4, the burnup was calculated for the flat geometry. A parallelepiped was considered. One side of 1.8 m was used as the side of the transverse section. The second side of 0.9 m was used as the length of the seed zone. Seed and breeding zone compositions were homogenized. In order to solve the transport equation, the $S_4$ approximation was used. The transport task at each burnup step was solved in two-group energy approximation; the energy of 0.0091 MeV that is the end of the fission spectrum was a boundary of group separation. Reflectors were taken into account by assigning buckling in both groups. The burnup was calculated at the constant temperature of the seed zone and breeding blanket taken equal to 1200 K.

Calculations using the MCU code for the 3D cylindrical reactor model in multi-groups consideration were carried out also assuming that temperature of all materials was equal to 1200 K. Burnup calculations were performed at a step of 100 days. Statistics for every burnup step is $10^6$ neutron histories. As a result of calculations, a neutron breeding ratio and fuel fission reaction rate were obtained for each burnup step. Figures 2–7 illustrate the results obtained.

Figure 2 shows plutonium concentration distribution (with respect to the initial concentration of loaded uranium) along the reactor core length at different moments of operation. It is seen that the concentration profile has explicit peaks that correspond to the wave burning region at particular moment of time. The plutonium concentration profile moves from the left boundary to the right one in time. The maximum relative plutonium concentration, which is achieved during the reactor cycle, is, as seen on the graph, 9%. This maximum is intrinsic of the profile at any moment of time after entering the wave mode.

Figure 3 shows relative $^{238}$U distribution along the core length at different moments of time. It is seen on the graph that fuel burnup can reach 70% (for initial cells). At an average, burnup in the core is ~50% after wave passage. Thus, $^{238}$U is used in these reactors more effectively than in any conventional fast reactor.

Figure 4 shows the wave behavior of reactor dynamics best of all. Energy release as a function of distance is a soliton that is a solitary wave. Such wave maintains the area under the curve and repeats
distinctly when the wave reaches the maximum value. Based on the results given in the figure it is seen that the speed of the wave for this case is ~10 cm/year.

Figure 5 shows a change in the multiplication coefficient during burnup. It is seen that for approximately 6 000 days the reactor is at the stage of entering the wave mode. This stage is stipulated by burning in the reactor seed zone, which plays the role of the external source.

Results also showed that burnup of $^{238}$U behind the wave front at the end of cycle (EOC) reaches 50–60% that is significantly higher than in conventional fast reactors even accounting for fuel recycling at operation in the closed cycle.

In addition, results of studies showed that in order to provide the multiplication coefficient higher that unit during the entire stage of fission wave generation and fuel burnup in the breeding zone it is expedient to supplement the wave with small quantity of fissile material (for instance, 0.2–0.3 % weight of $^{235}$U or $^{239}$Pu).
III. REACTOR WITH MOVABLE FUEL COMPOSITION

In this concept, wavelike movement of energy release in view of relativity of fuel and neutron flux movement is replaced by movement of the breeding material (fixed fission wave). Figure 7 shows a diagram of the reactor with the fixed fission wave. Spherical fuel elements are used with the meat made of metallic enriched uranium and metallic natural uranium with the ceramic (for example, silicon carbide) multi-layer coating that retains fission products. As the coolant, helium is used that allows for the harder neutron spectrum and more effective plutonium buildup.

The reactor consists of the seed zone with the enriched uranium ($U_{enr.}$), which supplies neutrons to the breeding zone made of natural uranium ($U_{nat.}$), where $^{239}$Pu builds up. After the necessary plutonium concentration is built up, energy release $Q$ displaces to the breeding zone. The height of the breeding zone is maintained with loaded fuel spheres containing the breeding material. Spent fuel in the seed zone can be gradually unloaded (the principle of single passage of fuel spheres through the core) or diluted with fuel spheres containing the breeding material and loaded again into the core (the principle of multiple passage of fuel spheres through the core). In order to stabilize the energy release field, the loading and unloading rate should be synchronized. The fuel sphere irradiation time and uranium burnup rate will be defined by fuel sphere operability limitations. Use of reactivity compensation rods partially inserted in the side reflector provides a possibility of modifying the axial power distribution along during fuel particle circulation. Fuel particle circulation-through-the-core options considered made it possible to define the following additional conditions for generating a...
stable nuclear burning wave, which would ensure additional loading of the breeding material (natural uranium) and multiplication coefficient stabilization:

- Reactor specific power should be high in order the required-quantity-of-$^{239}$Pu-generation (buildup) process took reasonable time (a few years). This process should not be comparable with the reactor lifetime (50–60 years). Specific power is 200–300 MW/m$^3$.

- Plutonium concentration, in addition to the fact that it should reach the critical value (6–7%), should be sufficiently uniformly distributed along the core height.

These conditions assume initial multiple circulation of newly loaded fuel spheres through the core until equilibrium critical plutonium concentration and sufficiently stable power distribution establish in it.

Accounting for the above conditions, calculations were performed using MCU for the 3D reactor model with the specific power of 200 MW/m$^3$ that has the core 1.5 m in diameter and ~5.6 m high that corresponds to the reactor thermal power of 2 000 MW. As the reflector, BeO 20 cm thick was used.

For studies, a composition was selected, of which the 60 cm high seed zone has 65% of fuel spheres with uranium enriched by up to 14% and 35% of fuel spheres made of natural uranium. Spherical fuel elements of ~10.8 mm in diameter had the 0.9 mm thick silicon carbide cladding. Homogenized composition is U/ SiC/He = 0.438/0.162/0.4 (uranium takes 70% of the fuel sphere meat).

Figures 8 and 9 show multiplication coefficient variation and power distribution for the core at entering the condition, where critical values of plutonium concentration become stable at multiple circulation of initial fuel. This condition is achieved in two cycles each lasting for 1500 days.

The multiplication coefficient reaches ~1.073 (Fig. 8) and axial concentration of $^{239}$Pu built up in the core (the ratio of $^{239}$Pu nuclear concentration to $^{238}$U initial concentration) varies from 6 to 6.5%. Maximum fuel burnup is ~15% at the average axial burnup of 13.4%.

Figure 8, which shows multiplication coefficient variation during burnup, corresponds to sequential loading of fuel spheres made of natural metallic uranium alloyed by plutonium.

![Fig. 8: Multiplication coefficient variation in the course of burnup and after refueling.](image)

Maximum burnup of initially loaded fuel spheres reaches ~40% h.a. in 10 000 days (~27 years). Maximum burnup of breeding fuel spheres added to the reactor every 3 000 days (~8.2 years) from the moment of loading to the moment of unloading from the reactor is ~38% h.a. The speed of fuel sphere displacement in the core is ~23 cm/year. Initial $^{238}$U burns up by ~41%.

Axial power distribution (Fig. 9) shows that before additional loading of breeding fuel spheres core power distribution is sufficiently uniform and sinusoidal. Before additional loading of breeding fuel spheres, energy release displaces to the core top (dashed lines). After additional loading, symmetrical nature of power distribution is restored (solid lines in the figure). Thus, at the stage of stationary burnup, power distribution displaces from the core center to the top and vice versa at the practically constant maximum irregularity coefficient equal to ~2.6.

During operation, the multiplication coefficient varies from 1.025 to 1.073. Calculation estimates showed that the reactivity specified can be compensated for by 4 control rods based on enriched boron carbide, which are placed in pylons.
Fig. 9: Axial power distribution variation during reactor operation:
1 – 3,000 days; 2 – 7,000 days (before additional loading); 3 – 7,000 days (after additional loading); 4 – 10,000 days (before additional loading); 5 – 10,000 days (after additional loading); 6 – 13,000 days (before additional loading).

IV. CONCLUSION

As a result of studies, conditions were defined that are described in the present paper for maintaining the operation mode for the fast core reactor. This core allows for replacement of the enriched uranium by the natural one and long-term stationary burning of it. These conditions are as follows:

- In order to build up the critical concentration of $^{239}$Pu, it is necessary to use dense fuel in the breeding zone. Metallic uranium or natural uranium composition alloyed with plutonium are most suitable for that. Many recent activities on substantiation of use of metallic uranium alloyed with plutonium and zirconium in reactors [6] indicate additional opportunities for implementing the wave mode of energy release.

- In order to ensure plutonium build-up in reasonable time, the reactor specific power should be 200–300 MW/m$^3$.

- The reactor with movable fuel sphere charging should have uniform axial $^{239}$Pu critical concentration distribution. Otherwise, the nuclear burning wave, which maintains the burnup mode, dies down fast. For this purpose, the reactor with circulating fuel should provide an operation period, during which $^{239}$Pu critical concentration would be distributed uniformly. From this moment, it is possible to replace the initial spent fuel with the natural uranium or alloyed one. It is expedient to use uranium alloyed with plutonium (up to 5% weight) to compensate for fission products built up.

The conditionally critical problem, the solution results of which are presented in this paper, does not take into account specificities associated with the reactivity feedback. These specificities are stipulated by fuel temperature and power variation at multiplication coefficient fluctuation within the equilibrium value of this ratio. Indeed, in case of negative feedback, the multiplication coefficient additionally stabilizes.

The main issue for implementing the wave-energy-release reactor — which ensures natural uranium burnup at the level of 50–60% and long-term cycle of 30–40 years — is radiation resistance of the fuel used. Use of micro fuel spheres with the silicon carbide claddings in fast reactors defines positive prospects of solving this issue. For gas-cooled reactors, this is associated with the primary pressure increase to minimize coolant pumping power.

REFERENCES