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Research Article

Prospects of creation of the two-component nuclear energy system*

Andrey Yu. Petrov[1], Alexander V. Shutikov[1], Nikolay N. Ponomarev-Stepnoy[1], Valery S. Bezzubtzev[1], Mikhail V. Bakanov[1], Vladimir M. Troyanov[1]

1 *JSC "Rosenergoatom Concern", 25 Ferganskaya str., Moscow, 109507 Russia*

Corresponding author: *Vladimir M. Troyanov* (troyanov-vm@rosenergoatom.ru)

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Abstract

Possible options of organization of two-component energy system with closed nuclear fuel cycle (CNFC) and new business potential associated with provision of CFC services to foreign customers are examined.

Dominating role in the development of nuclear power generation is assigned to VVER reactors with gradually increasing fraction of sodium-cooled fast breeder reactors (FR) incorporated within the joint nuclear fuel cycle operated on MOX-fuel.

Components of such energy system perform the following functions:

1. Fast reactors:

- Generate electric power in base-load mode (possibility of fine tuning of reactor power within limited range (100 – 75 – 100%) is assumed);
- Utilize waste and/or regenerated uranium for re-fueling power reactors, produce plutonium applicable to the maximum extent for manufacturing MOX-fuel for VVER reactors;
- Incinerate long-lived highly radioactive wastes – minor actinides separated during reprocessing spent nuclear fuel of FR and VVER reactors.

2. VVER reactors:

- Generate electricity in compliance with manoeuvrability requirements imposed by the utility company operating the energy system;
- Utilize MOX-fuel instead of UO_2 fuel;
- Are offered for export with the option of returning SNF back to Russia;
- Plutonium extracted from VVER spent fuel is used for manufacturing MOX-fuel for SFR.

3. Nuclear fuel cycle facilities:

- Provide reprocessing of SNF from VVER and SFR with extraction of nuclear materials for recycling;
- Use depleted or reprocessed uranium and plutonium extracted from spent nuclear fuel for manufacturing MOX-fuel;
- Provide partitioning of RAW for subsequent utilization of minor actinides and reduction of risks of proliferation of nuclear materials, conditioning and disposal of RAW.

Russia possesses capacities for establishing the two-component system with CNFC, as well as the new business approach to rendering CNFC services to foreign customers.

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Keywords

Two-component nuclear energy system, centralized nuclear fuel cycle, commercial power supply complex of the Supplier (Rosatom)

1. Present status of nuclear power generation in Russia

As of today Rosatom Concern operates 36 NPP power units with installed capacity of 30.3 GW; here, capacity of power units equipped with VVER reactors amounts to 17.9 GW, that of RBMK reactors is equal to 11 GW and fast reactor capacity is equal to 1.4 GW. Power units designed in Russia with total capacity of about 28 GW are currently in operation abroad Russia.

The level of failures on the operated NPPs observed during recent years does not exceed the levels established by the first INES Scale. Nuclear power units newly put into operation belong to Generation 3+ reactors.

Energy Strategy of Russia for the period until 2015 provides for the preservation of the fraction of nuclear power in the total generation of electricity in the country at the level of 18%. Installed capacity of NPPS may amount in such case to 38 GW.

Taking into account decommissioning of RBMK reactors, the main contribution in the generation of electricity will be made by power units equipped with VVER reactors of new generation.

2. Creation of two-component energy generating system – development strategy

Solution of the problem of SNF taking into account SNF delivered from foreign power units, as well as enhancement of their financial competitiveness is the pre-condition of development of nuclear power generation.

The Rosatom Program of Innovation Development provides for the beginning of creation of two-component nuclear energy generation system on the basis of VVER and SFR reactors (Shutikov 2017, Petrov 2018, Klinov et al. 2018, Alekseev et al. 2016). The layout of arrangement of NPP power units until 2035 (Executive order of the Government No. 1209-r dated June 9, 2017) providing for the construction of BN-1200 power unit on the site of the Beloyarsk NPP was adopted by the Government of the RF.

Commissioning of BN-800 and utilization of MOX-fuel in this reactor followed by subsequent reprocessing and fabrication of fresh MOX-fuel constitute together with the perspective construction of power units with BN-1200 reactors the beginning of formation of two-component nuclear power generating system.

Taking into account the extension of their service life already commissioned NPPs with VVER reactors will continue to be in operation beyond the end of XXI century.

Although VVER technology (first component of the two-component nuclear energy generating system) is well proven and reliable, it requires, however, further enhancement of financial performance. Already operated and designed VVERs can partially or completely utilize plutonium bred in fast reactors, thus replacing ^{235}U as nuclear fuel.

With commissioning of BN-800 and positive experience of operation of BN-600 the basis was laid for further development of BN technology, as well as the development of pilot technologies for closing nuclear fuel cycle. As of today, BN technology is ready for commercial implementation.

Advanced nuclear power units with BN-1200M reactors can form the basis for the second component of the two-component nuclear energy generating system.

It has to be noted that the development of BN technologies in the two-component nuclear energy generating system combine optimally with VVER SNF reprocessing as the source of plutonium for fueling BN reactors. In such case, the first BN power unit serves as the basis for provision of plutonium fuel for VVER power units. Layout of mutual fuel support of VVER and BN reactor units is shown in Fig. 1.

The proportion between BN and VVER reactors in such system is determined by the strategy of development of nuclear power generation under implementation and its provision with raw materials. Such proportion is schematically shown in Fig. 2.

The advantage of the two-component nuclear power generating system is the fact that it will ensure financial efficiency of nuclear power generation system due to the following:

- Utilization of virtually unlimited potential of waste and natural uranium as the source of nuclear fuel makeup for BN and VVER reactor fuel cycle as opposed to inescapable deficit of uranium and continuous increase of cost of uranium in the case of one-component option;
- Elimination of accumulated stock of plutonium;
- Reduction of volumes of accumulated SNF as the result of its reprocessing and recycling of nuclear materials and saving costs for the Rosenergoatom Concern under liabilities for handling SNF;
- Reduction of activity of radwastes and their volumes due to the incineration of long-lived minor actinide radwastes in BN reactors;
- Plutonium breeding in BN reactors and its utilization in the form of MOX-fuel for VVER reactors.

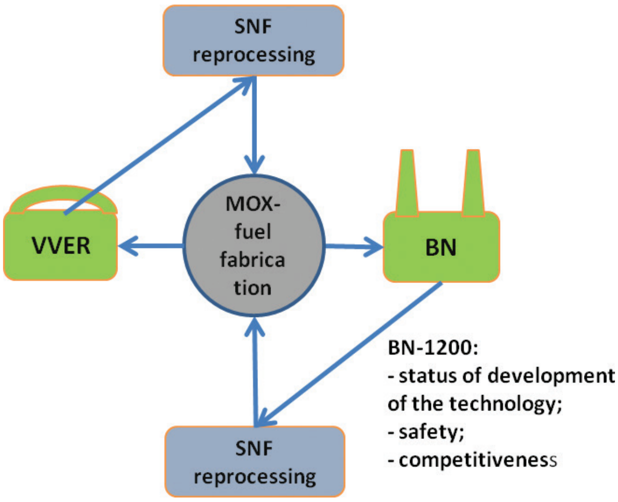

Figure 1. Layout of mutual fuel support of VVER and BN.

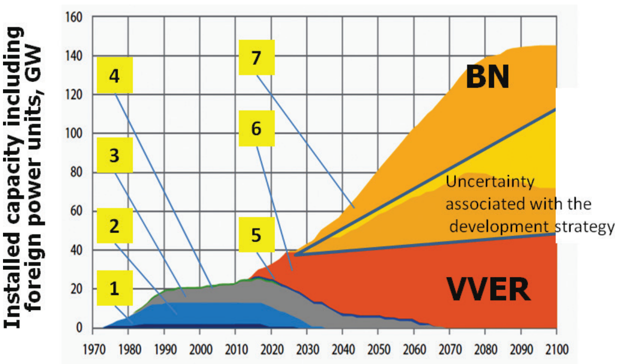

Figure 2. Proportion between BN and VVER reactors in the two-component nuclear power generating system: 1 – VVER-440; 2 – RBMK; 3 – VVER-1000; 4 – BN-600; 5 – BN-800; 6 – VVER-TOI; 7 – BN-1200.

Beside the above, the suggested nuclear power generating system will open new possibilities for the Rosatom State Corporation on the foreign markets due to the following:

- Export of VVER reactors jointly with "leasing" nuclear fuel;
- Commercial and scientific cooperation in the development of BN technologies;
- Provision of additional services as pertains to the storage and reprocessing of SNF from foreign NPPs with subsequent utilization of separated materials in BN reactor cores.

3. Roles played in two-component nuclear power generating system BN reactors

- Generate electricity in base load mode; possibility of adjustment of power level within limited range of 100 – 75 – 100% is assumed;
- Use accumulated waste or regenerated uranium for nuclear reactor fuel makeup; produce plutonium suitable to the maximum extent for fabrication of VVER MOX- fuel;
- Incinerate long-lived minor actinide high-activity wastes separated during reprocessing SNF from BN and VVER reactors.

4. VVER reactors

- Generate electricity in the mode complying with requirements pertaining to the reactor control adjustability imposed by the systems operator;
- Partially utilize MOX-fuel instead of fuel fabricated from UO_2;
- Are supplied to foreign countries with provision of services pertaining to the return of SNF to Russia;
- Plutonium separated from VVER SNF is supplied for manufacturing MOX-fuel for BN reactors.

5. NFC facilities

- Ensure reprocessing of VVER and BN SNF, extraction of nuclear materials for recycling;
- Utilize waste and regenerated uranium and plutonium extracted from SNF for manufacturing MOX-fuel;
- Ensure fracturing of radwastes for the purpose of subsequent utilization of minor actinides and reduction of risks of NM proliferation, conditioning and final disposal of radwastes.

6. Degree of development of technologies of fast sodium-cooled reactors

Development of BN technologies was conducted in Russia during 60 years (Fig. 3).

BN-600 power unit demonstrates accident-free operation during already 35 years with average duty factor reaching 77.55%, and maximum achieved duty factor of 87.45 %. Design probability of severe accident (accompanied with reactor core damage) after implementation of extension of reactor service life is equal to $3.5 \cdot 10^{-5}$ per year.

BN-800 has design duty factor of 85%. Calculated probability of severe accidents is equal to $2 \cdot 10^{-6}$ per year.

The developed design of advanced power unit with BN-1200M reactor ensures the following:

- Improvement of operational and financial performance;
- Exclusion of the necessity of evacuation of people in case of accidents;
- Probability of severe damage of reactor core less than $1 \cdot 10^{-6}$ per reactor per year;
- Retention of reactor core elements damaged in the course of accident inside the reactor vessel.

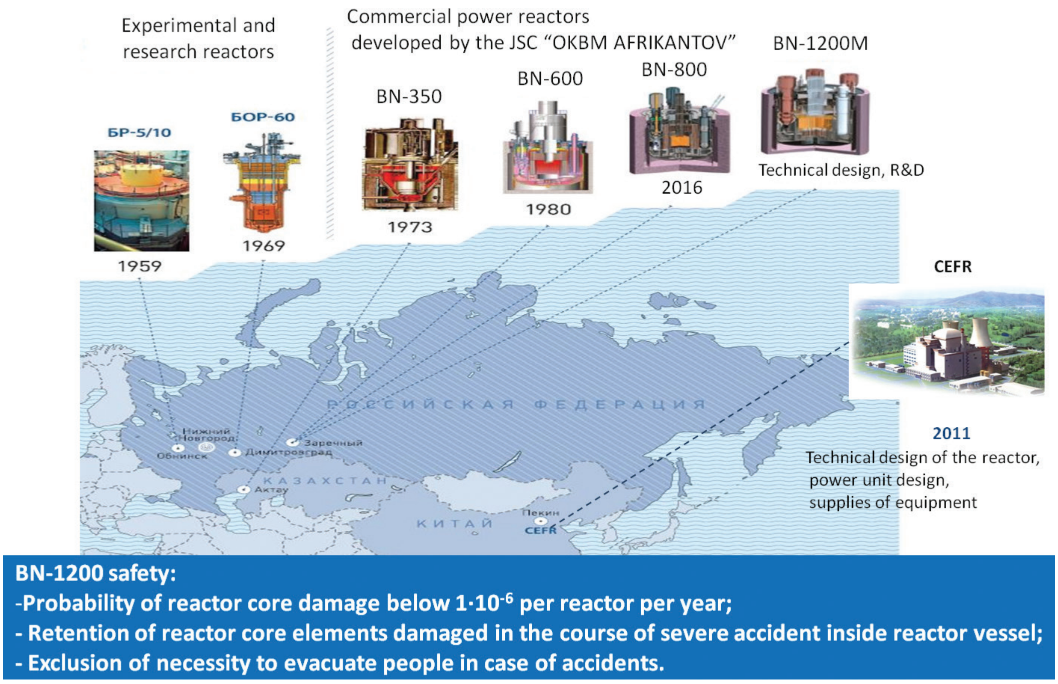

Figure 3. Status of development of BN technologies in Russia.

7. Selection of fuel compositions for two-component nuclear power generating system

Use of nuclear fuel with high values of operational reliability, power yield and the perspective of enhancement of already reached technical and financial performance parameters is the mandatory condition for the Concern as the utility organization.

As of today, uranium oxide and MOX fuel correspond to the above requirements.

Cost of manufacturing MOX-fuel is lower as compared with MNUP-fuel while reference burnup and power yield is higher for MOX-fuel.

For reducing the cost of NFC in two-component nuclear power generating system the target is the use of unified MOX-fuel for both components of the nuclear power generating system which implies the use of similar types of equipment and technologies required for production of fuel for both VVER and BN reactors. In such case, the technology must be the most straightforward and referable.

The Concern participates in the development of innovation fuel compositions, as well as of MNUP-fuel and, in case of reaching by the studies of MNUP-fuel of sufficiently high level; the Concern is ready to start using this fuel.

8. Selection of the type of NFC organization: centralized NFC

It has to be taken into consideration that NPPs in Russia are arranged in the close vicinity of consumers of electricity where construction of various production facilities for manufacturing and reprocessing nuclear fuel is not possible.

The expediency of reprocessing VVER SNF from NPPs distributed over the territory of the country and from foreign SNF sources requires centralization of reprocessing production capacities using already existing NFC facilities, such as FSUE “PO MAYAK”, JSC “SKhK” or FSUE “GKhK”. It is quite natural that in such case reprocessing of SNF from BN reactors has to be organized at the same place at the centralized production facility.

Such approach is in correspondence with all requirements of regulatory documents in the field of use of nuclear energy as pertains to separation of functions of entities operating NPPs and NFC production.

It has to be taken into consideration here that economics of large-scale centralized NFC production is preferable compared to low-productivity production within the nuclear fuel cycle structure adjacent to the NPP.

Layout of centralized (distributed among separate sites) NFC within the two-component nuclear power generating system is presented in Fig. 4.

9. Option of international cooperation: centralized NFC in Russia – NPPs abroad Russia

Operation of two-component nuclear power generating system with closed nuclear fuel cycle planned to be organized with participation of foreign consumers is shown in Fig. 5. The case when Russian production facilities provide complex services for reprocessing SNF from NPPs with VVER reactors constructed by Rosatom Corporation

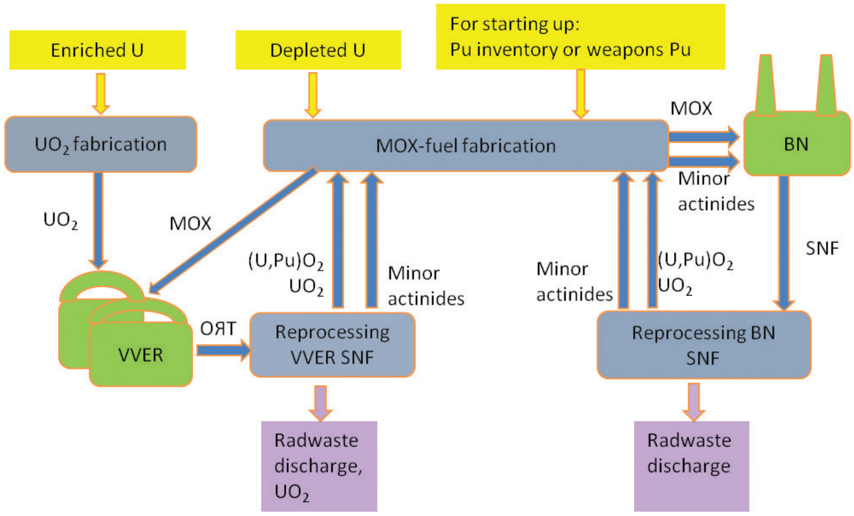

Figure 4. Layout of centralized (distributed over separate sites) NFC within two-component nuclear power generating system.

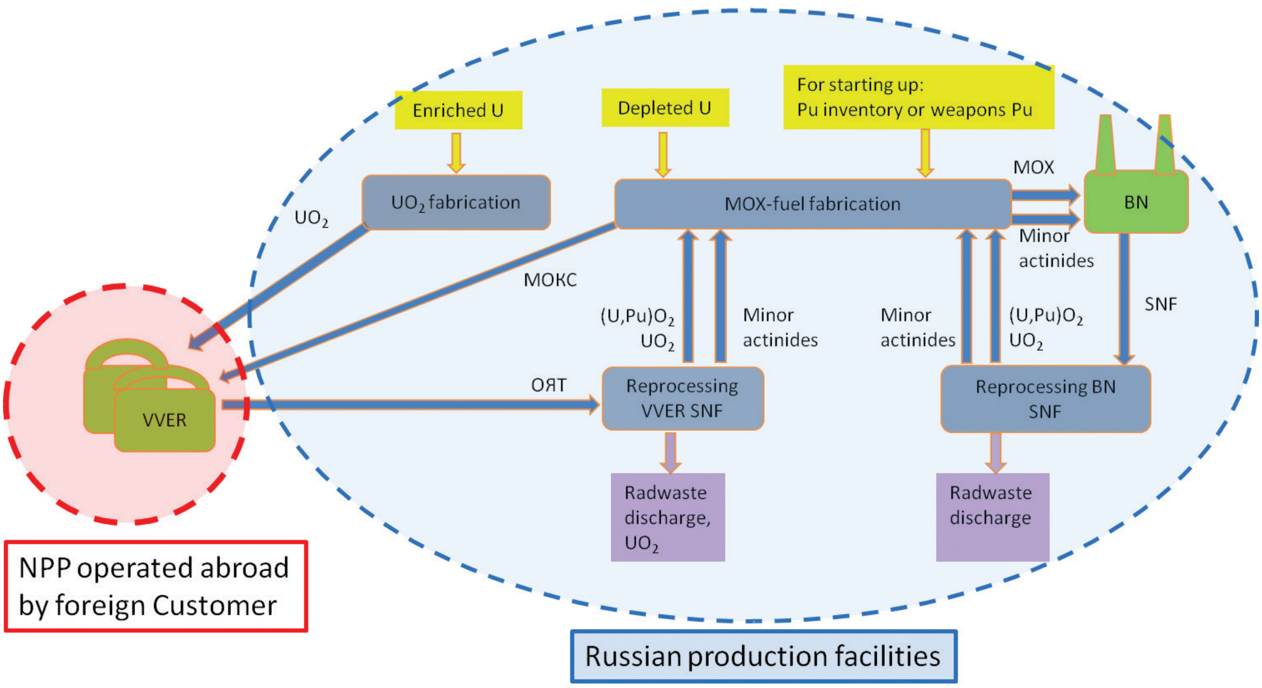

Figure 5. Organization of operation of two-component nuclear power generating system with closed nuclear fuel cycle with participation of foreign customers.

abroad Russia and fabrication of fresh nuclear fuel using regenerated nuclear materials is shown here.

The main principle amounts to the fact that foreign Consumer (NPP) must be saved the necessity to solve the problems of long-term storage of SNF or SNF reprocessing in the conditions of closed nuclear fuel cycle. This refers, in the first place, to Consumers operating limited number of power units and not planning to establish full-scale nuclear industry.

Foreign Customer is offered to simply use a power unit equipped with advanced VVER-1200 reactor for supporting which during the whole reactor lifespan the Supplier provides services on the supplies of nuclear fuel with subsequent returning of irradiated fuel back to Russia. The centralized closed nuclear fuel cycle, and BN-1200 power units remain within the sphere of responsibility of the Supplier (Rosatom State Corporation) on the Russian territory.

Different options of organization of handling products generated in the process of reprocessing SNF received from the foreign Customer:

- Retrieval of conditioned radwastes, provision of services on the storage of separated materials until the decision with regard to their further handling is made;
- Retrieval of conditioned radwastes and part of separated nuclear materials in the composition of fresh nuclear fuel, storage of minor actinides until the decision with regard to their further handling is made;

- Retrieval of conditioned radwastes, provision of services on the incineration of minor actinides in fast reactors and, partially, on their technological storage, return of equivalent quantity of separated nuclear materials in the composition of fresh nuclear fuel;
- Independent decision making by the Supplier of nuclear fuel with regard to all emerging issues in the case when fuel is supplied to the Customer on lease.

10. Expected timeframe for the development of technologies for the two-component nuclear power generating system

Expected timeframe for the development of the two-component nuclear power generating system is presented in Fig. 6.

11. International trends in the selection of paths for the development of nuclear power generation. Conclusions

The above-described strategy of development of nuclear power generation is, in principle, in concurrence with worldwide trends. All sources cited in (Zhang 2017, Pivet 2017, Laugier 2019, Bhaduri and Puthiyavinayagam 2017, Sagayama 2017) (authorized representatives of China, France, India, Japan) provide for the strategic development of nuclear power generation in their respective countries in the form of two-component system based on PWR and sodium-cooled fast nuclear reactors. Conclusion can be drawn based on the analysis of works conducted in the USA on the development of VTR test sodium-cooled fast reactor (Heidet 2019) that the USA is returning to the ideology of development of fast reactors within the structure of the national nuclear power generation.

Roles assigned to thermal and fast nuclear reactors within the two-component nuclear power generating system coincide with the strategy of development of nuclear power generation in Russia described above. The differences refer at the present moment only to Korea and the USA intending to use the technologies of metal uranium-plutonium-zirconium fuel in fast reactors.

As of the present moment Russia goes ahead of other countries with regard to the degree of its preparedness to the implementation of two-component nuclear power generating system with closed nuclear fuel cycle by virtue of the fact that it has experience of development and operation of BN-600 and BN-800 nuclear power units, already developed design of BN-1200 reactor and operated facilities for reprocessing irradiated nuclear fuel. Using this advantageous position Russia has possibilities to establish and offer on the markets of the new business associated with provision of CFNC services to foreign customers.

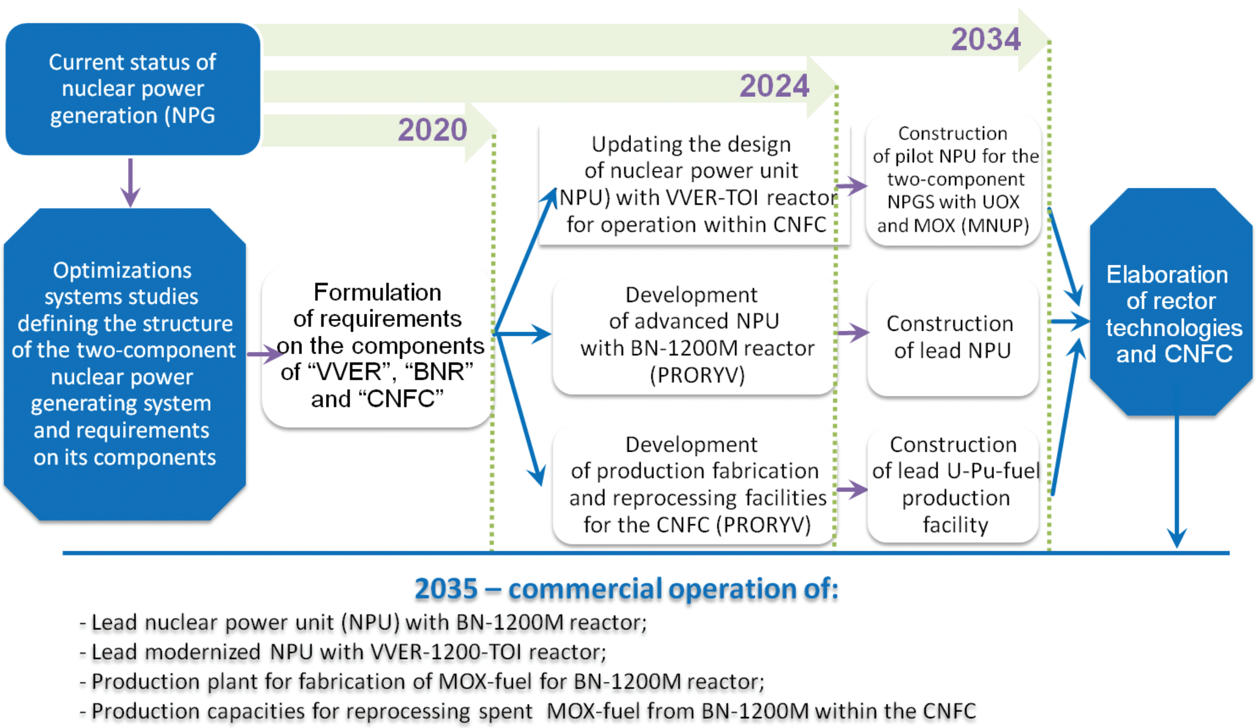

Figure 6. Expected timeframe for the development of the two-component nuclear power generating system (UOX – uranium oxide fuel, MNUP – mixed nitride uranium-plutonium fuel).

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