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Development of the general design of the industrial energy complex with CNFC

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Abstract. The article discusses the technological and project aspects of the closure of the nuclear fuel cycle of fast neutron reactors on the example of the conceptual design of the industrial power complex. The advantages of using combined SNF processing technology are noted. The advantages of creating a universal production of nuclear fuel for fast neutron reactors of different configurations are given. Hypothetical sites for the production of closed nuclear fuel cycle are considered.

1. Introduction

The closure of nuclear fuel cycle for fast neutron reactors is one of the development priorities for the nuclear power industry in the world. The key requirement to close the nuclear fuel cycle is to provide integrated safety, competitiveness and sustainability, which are a must for a full-scale development of nuclear power industry [1].

A representative comparison of the existing competitive options for process solutions must be performed to choose the method of technological implementation of such an integrated approach to create a closed nuclear fuel cycle [2]. The selection is additionally complicated by the fact that the existing process solutions are at a different level of elaboration, for example, the hydrometallurgical technology based on the Purex process is an industrial technology of reprocessing spent nuclear fuel. Also, the world has accumulated considerable experience in the development of pyrochemical technologies for reprocessing of spent nuclear fuel in salt melts. Nevertheless, the existing limitations of hydrometallurgical and pyrochemical technologies have become the reason for developing a combined (pyro-hydrometallurgical) technology, which allows to obtain a synergistic effect from using the advantages of pyrochemical and hydrometallurgical technologies, thus providing for processing of spent nuclear fuel with a short residence time and obtaining the target product with high fission products (FP) purification rate.

The same applies to existing technologies for the production of uranium-plutonium fuel, which impose requirements on the parameters of recycled products of spent nuclear fuel reprocessing.

Since competitiveness is one of the key criteria for choosing the method of the nuclear fuel cycle closure, the site to locate the production facilities and the method of implementation (on-site stationary or centralized) of the nuclear fuel cycle also require justification [3].

This paper considers using the concept design of closed nuclear fuel cycle (CNFC) production sites as a tool for performing multi-criteria analysis.

IOP Conf. Series: Journal of Physics: Conf. Series **1475** (2020) 012007 doi:10.1088/1742-6596/1475/1/012007

2. General design of the Industrial Power Complex with CNFC

The general design is the state of the minimal development of a facility with focusing on key parameters only, allowing to evaluate its main final technical and economic indicators. An integral attribute of the concept design is a 3D-model.

The idea of the general design requires consideration of various options for implementing the facility in a limited time frame, highlighting critical areas of optimization.

Such concept design is implemented to develop a technically and economically sound choice of basic technical solutions for (CNFC) technology and production for a subsequent design ofthe Industrial Power complex (IEC) with taking into account the requirements of ensuring competitiveness, minimizing capital and operating costs and production costs of nuclear fuel.

An integral part of developing the general;design is a program of research and development (R&D) work.

Joint optimization of process, design and engineering solutions shall be made to achieve the required criteria, including developing universal technologies for the manufacture of mixed oxide and nitride uranium-plutonium fuel, reprocessing of mixed oxide and nitride uranium-plutonium spent fuel, as well as radioactive waste management.

The production diagram of the CNFC IEC and the structure of the material flows are shown in figure 1.

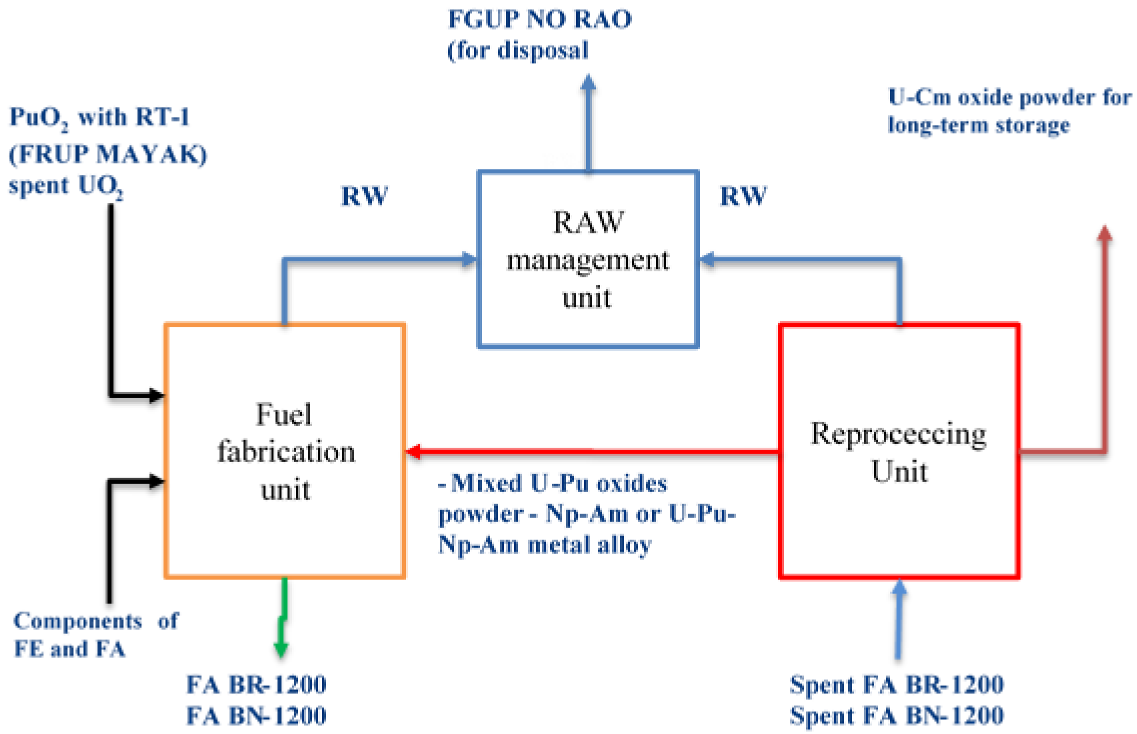


Figure 1. Production diagram of the CNFC IEC and the structure of the material flows.

It is assumed that 3 power units with BN/BR-1200 RP are commissioned in sequence while developing the general design of Industrial Power Copmlex with CNFC

Nuclear fuel production should ensure the manufacture of fuel assemblies of the initial load for BN-1200 and BR-1200 reactors, as well as the fabrication of fuel assemblies for subsequent refueling with the inclusion of minor actinides for transmutation in the fuel composition.

Process lines should provide the BN-1200 and BR-1200 reactors with fuel in the following configurations:

- MOX for BN-1200 reactor;

- MNUP for BR-1200 reactor;
- MNUP for BN-1200 reactor;

The development of process lines requires optimization of the performance, quantity and range of equipment ensuring the specified production performance in general in order to reduce the construction and operation costs of the industrial energy complex. A scheme has been developed for manufacturing MOX and MNUP fuel in fuel elements and fuel assemblies for BR-1200 and BN-1200 reactors for this purpose being as much universal as possible. The scheme is shown in figure 2.

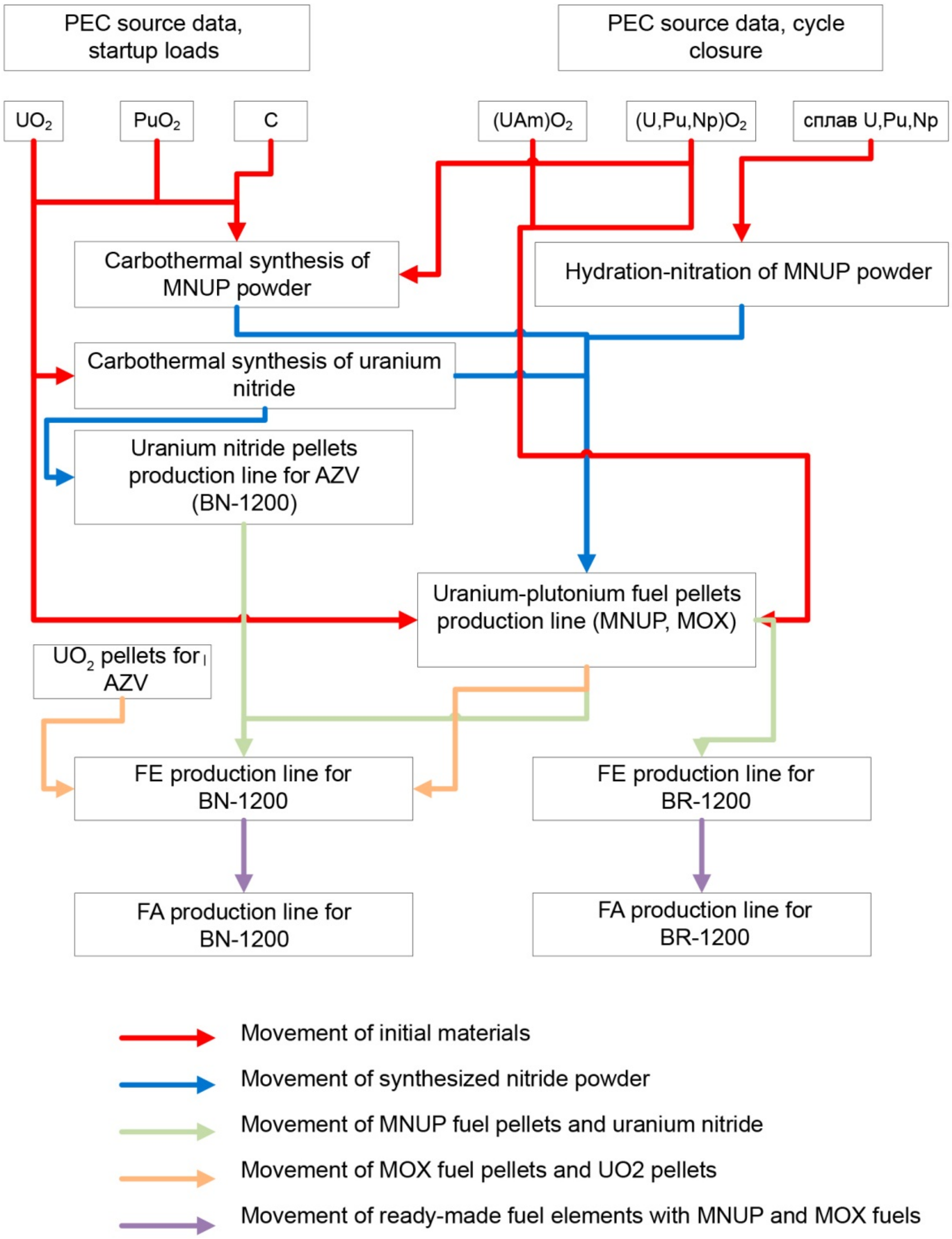


Figure 2. Process flow chart of the universal nuclear fuel production.

When choosing a technology for processing spent nuclear fuel, the process scheme was conventionally divided into 3 blocks — first production stage, main process operations, and the final product manufacture

The head process stage is common for all considered options of SNF processing scheme. Figures 3-5 show the keydiagrams for SNF reprocessing.

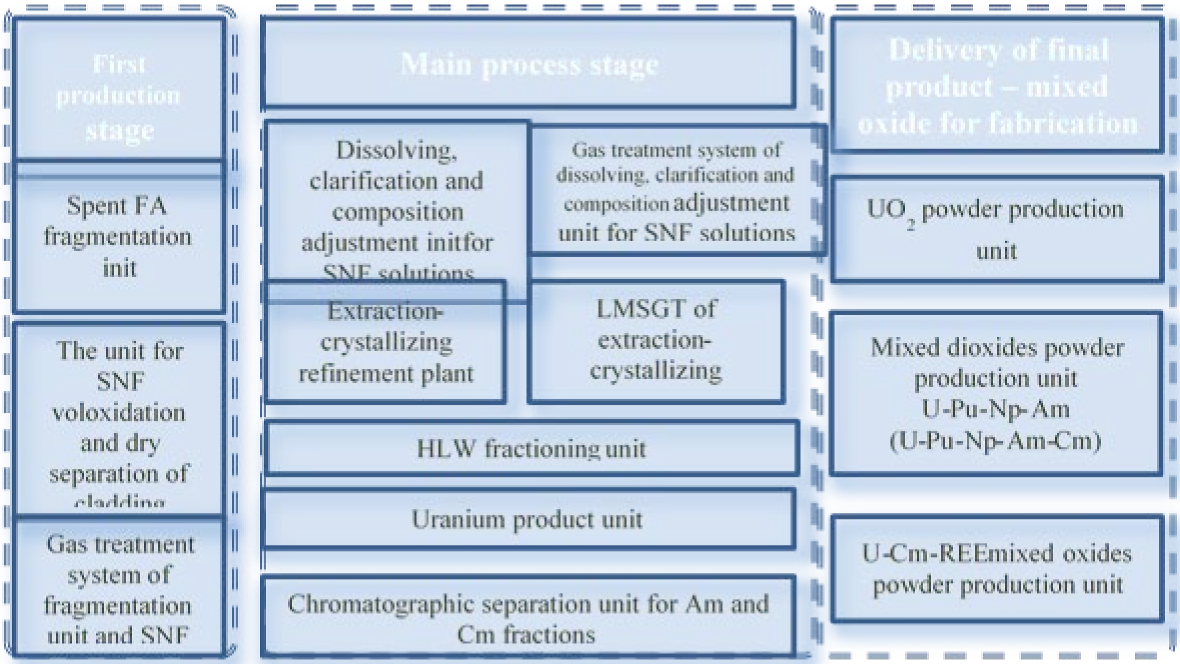


Figure 3. Keydiagram of hydrometallurgical processing of SNF.

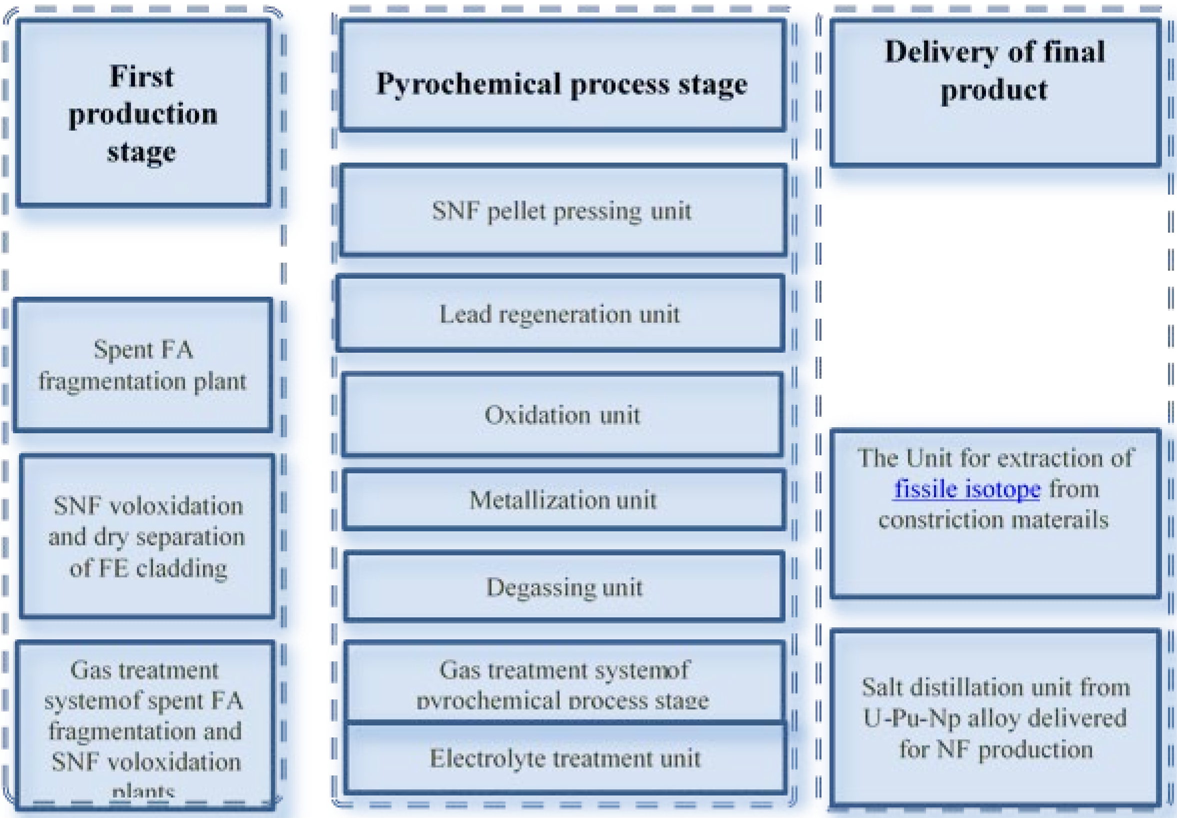


Figure 4. Key diagram of pyrochemical processing of SNF.

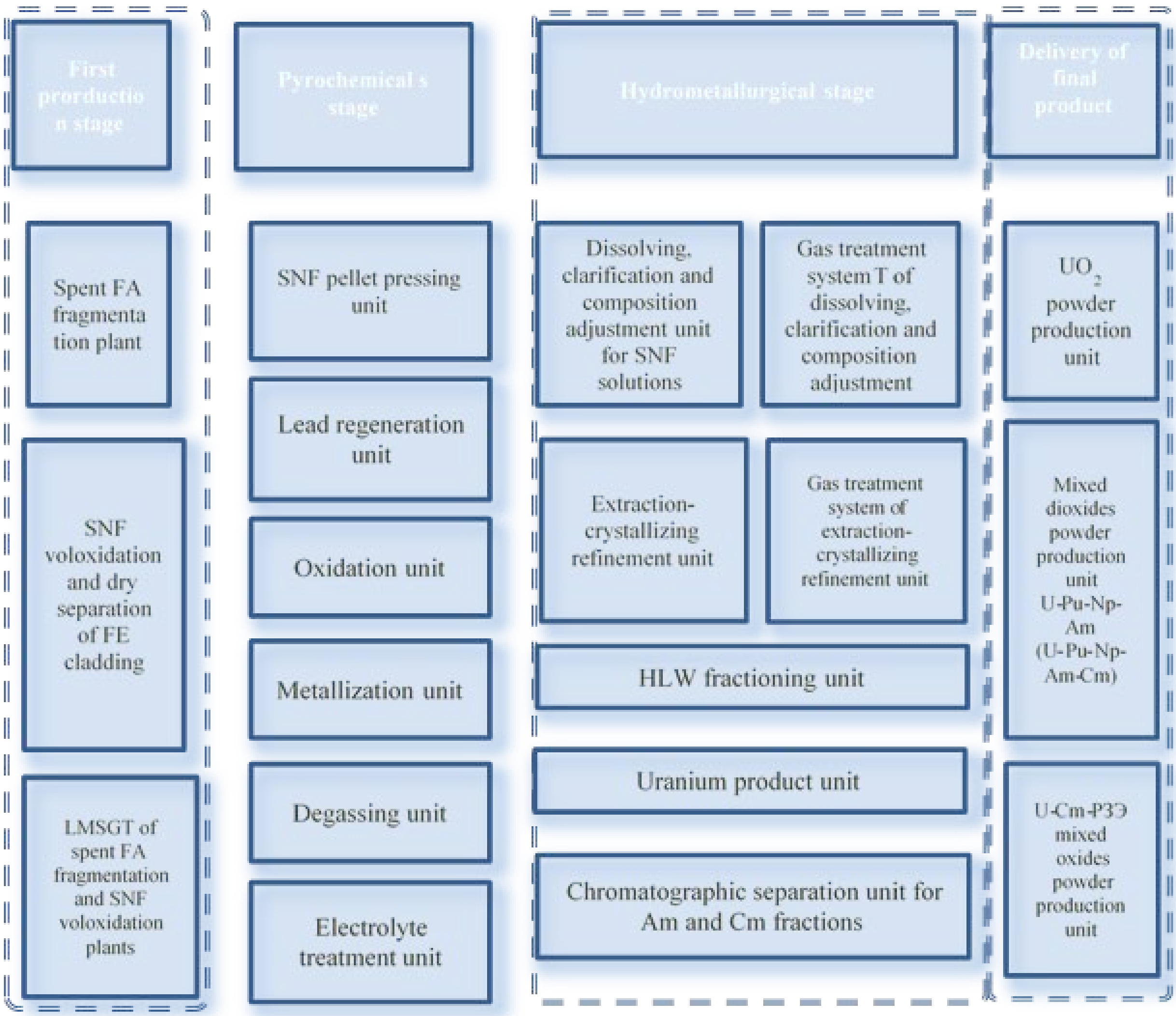


Figure 5. Key diagram of combined pyro-hydrometallurgical processing of SNF.

The difference between the pyrochemical sections in the combined technology and the "pure" pyrochemistry lies in the fact that for the "combined option does not have 4 process stages:

- pellet manufacture and re-metallization section;
- re-metallization;
- refining and fractioning;
- oxidation of recycled products.

Also, hydrometallurgical processing is significantly simplified.

Due to the requirements for safety, minimization of capital and operating costs, the minimization of accumulated SNF and fissile materials, possible maintenance of residual fissile material content in RW at a required level, the key factors include the production compactness (figure 6), the possibility of processing SNF with a short pre-decay time, the possibility of additional extraction of fissile material from flows sent to RW.

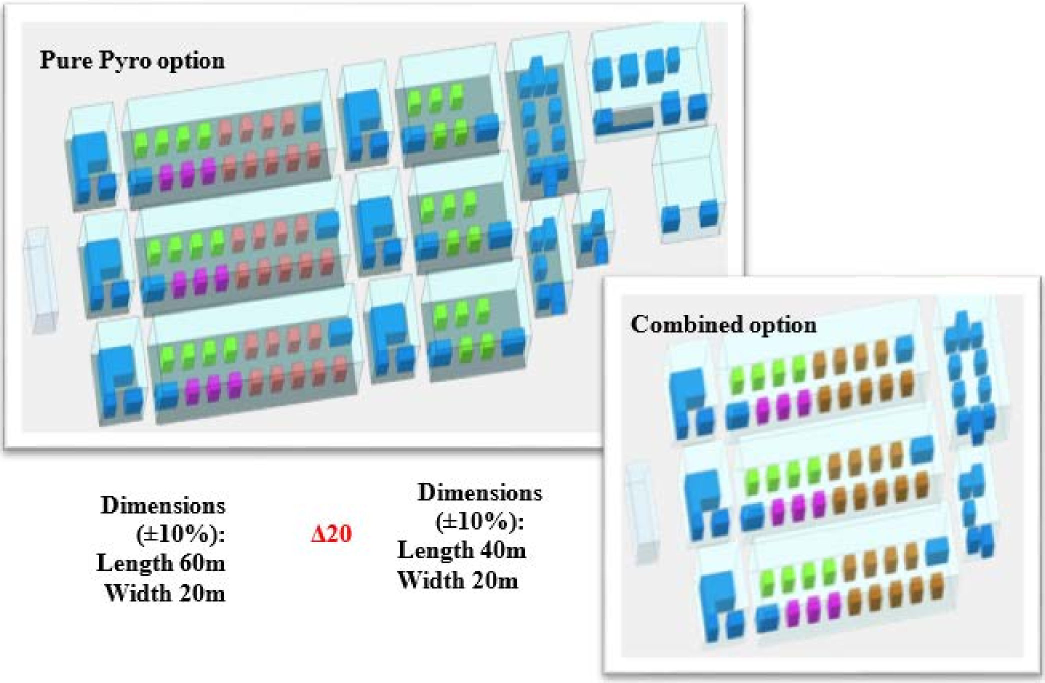


Figure 6. Comparison of pyrochemical sections of SNF processing between pure pyrochemistry and combined technology.

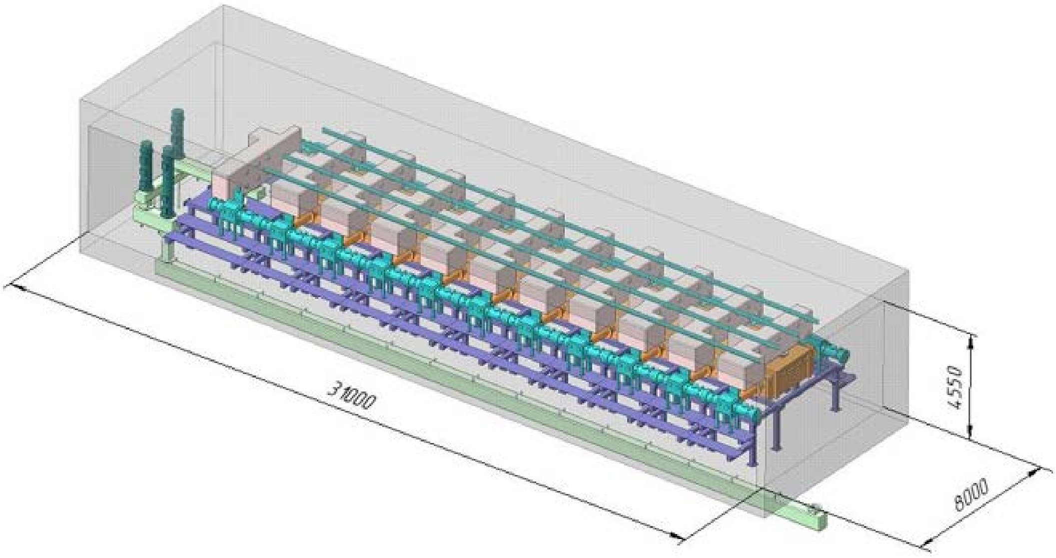
At current R&D level the combined technology meets the requirements and allows by using small-size pyrochemical units to reprocess high-burned SNF and extract fissile materials out of flows which are going to nuclear waste.

It should be noted that since the target products of the combined technology are oxides, the application of carbothermal synthesis of mixed uranium-plutonium is advisable for the manufacture of nitride nuclear fuel from regenerated products. The same applies to the hydrometallurgical technology. At the same time, it is advisable to use the method of hydrogenation-nitration for metals alloys from pyrochemical technology. Other options require the use of additional conversion steps, which make 100% yield of the product unlikely.

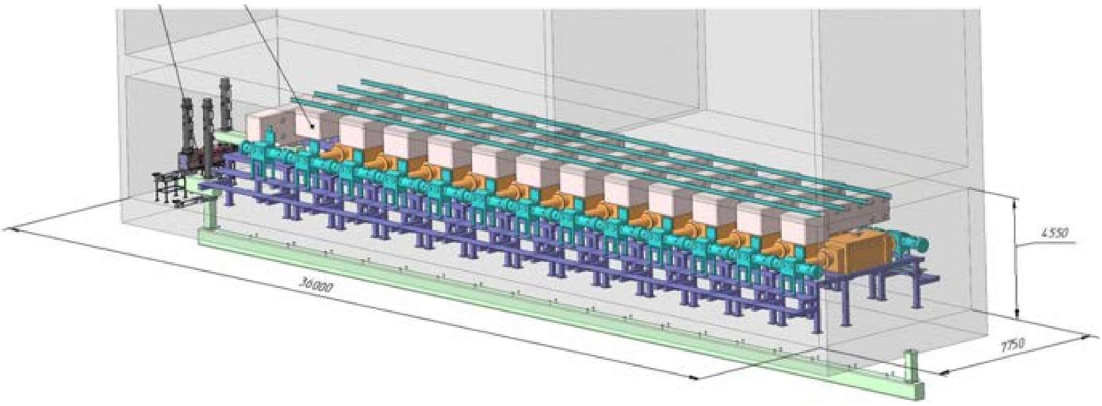
The advantage of hydrogenation-nitration method is the small-size equipment, lower temperature of the synthesis process and, hence, lower energy costs. The disadvantage inlcudes the need to use hydrogen to hydrogenate metallic uranium and plutonium, which is explosive and fire hazardous and does not fully comply with the principles of natural safety postulated in the PROTYV project.

A schematic representation of sections for hydrogenation-nitration and carbothermal synthesis is shown in figure 7.

Sections are described in table 1.



(a) hydrogenation-nitration section



(b) carbothermal synthesis section

Figure 7. Dimensions Overall drawing of the hydrogenation-nitration section and carbothermal synthesis section.

Table 1. Comparison of parameters for manufacturing sections of mixed uranium-plutonium nitrides as per carbothermal synthesis and hydrogenation-nitration technologies

Carbothermal synthesis section			Hydrogenation-nitration section		
Installed capacity, kW	Dimensions, LxWxH, m	Weight, kg	Installed capacity, kW	Dimensions, LxWxH, m	Weight, kg
908	36x7.8x4.5	110000	100	31x8x4.5	100000

The concept of on-site closed nuclear fuel cycle involves a joint use of the production site infrastructure for both the power unit and for the nuclear fuel production and reprocessing of spent nuclear fuel.

This also applies to radioactive waste management facilities. The technologies considered within the framework of the general design generate a wide range of radioactive waste, which leads to the need to unify the applied methods of RW conditioning to the maximum extent to reduce the number of operating facilities.

Figure 8 shows the diagram of RW management from the production of MNUP and MOX fuel and processing SNF of BN-1200 and BR-1200 reactors.

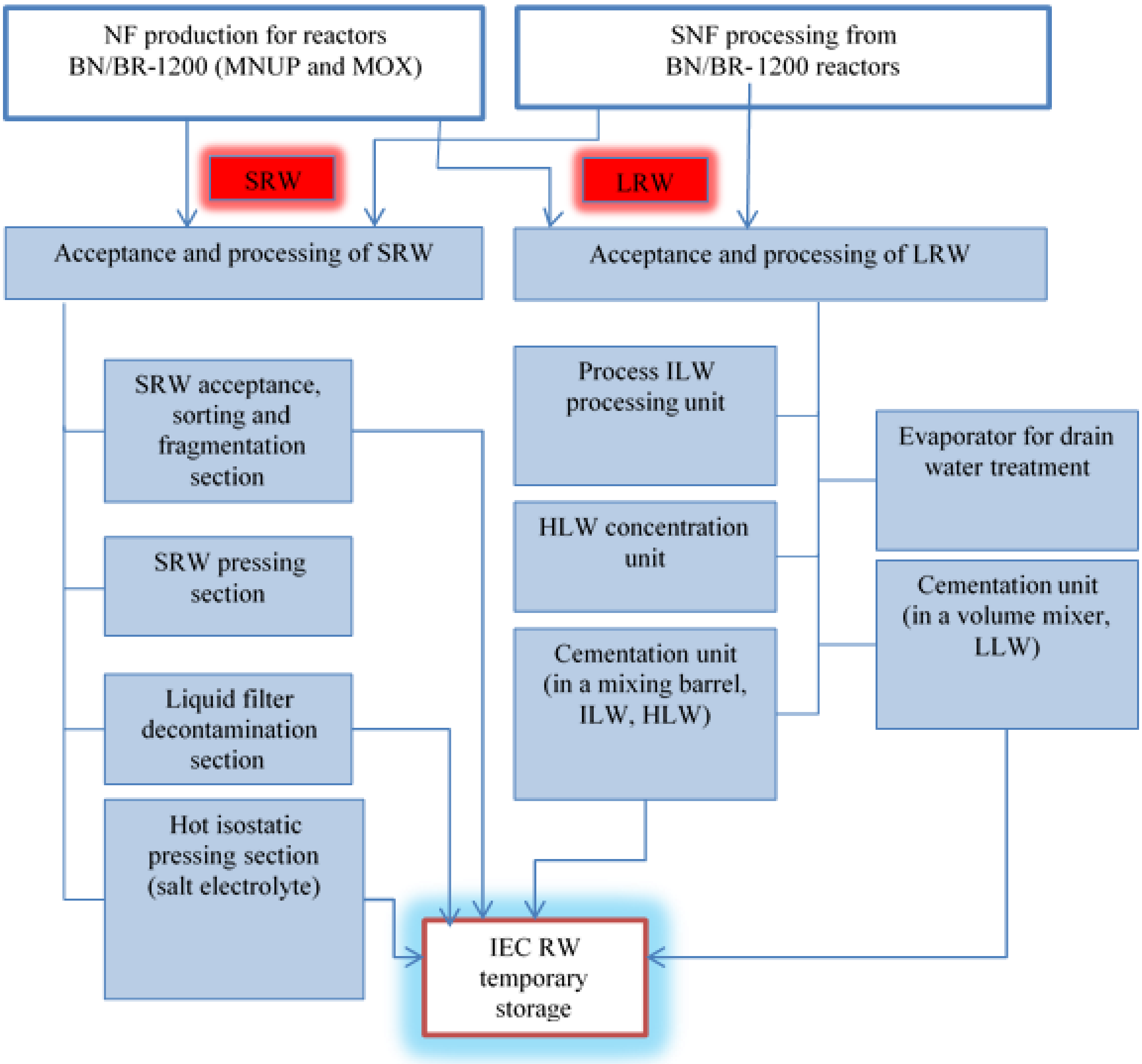


Figure 8. Key diagram of RW management.

When developing the general design to reduce the volume of secondary RW and the cost of facilities, it was decided to consider a possibility of reducing high-temperature processes of RW conditioning

An analysis of the current state of development in this area has shown there are pre-conditions for using the cementing method not only for grouting LLW and ILW categories of radwaste, but for high level waste as well.

The advantage of application this approach is a possibility to use the same unit for LRW (both aquatic and organic) and for SRW. In addition, the disposal of secondary waste is also possible by using the grout treatment unit.

IOP Conf. Series: Journal of Physics: Conf. Series **1475** (2020) 012007 doi:10.1088/1742-6596/1475/1/012007

However, because of IAEA recommendations it is required to have separate unit for HLW conditioning.

The comparison of proposed approach with vitrification methods should be fulfilled within the framework of general design using comparable criteria to select the best decision.

The development of general design supposes best application oa existing manufacture in case to decrease the capital costs.

It was decided to consider the feasibility of locating production facilities of the Industrial Power Complex with closed nuclear fuel cycle on the sites of SCC JSC, FGUP GHK FSUE Mayak and the site of the South Ukrainian NPP.

Options of using nuclear fuel fabrication and SNF reprocessing technologies in relation to the production sites is given in table 2.

Table 2. Location of IEC CNFC production facilities with taking in account process arrangement on the production sites.

Option No.	Site	Fuel cycle organization	Technology		
			Fuel fabrication		Fuel processing
			Fuel type	Technology	
1	**SCC**	Centralized NFC	MNUP BN-1200	CTS	Combined
			MNUP BR-1200	CTS	
2	**Mayak**	Centralized NFC	MOX BN-1200	MOX fuel	Hydro
			MNUP BR-1200	CTS	
3	**SU NPP**	On-site NFC	MNUP BN-1200	CTS	Hydro
			MNUP BR-1200		
4			MNUP BN-1200	CTS	Hydro
			MNUP BR-1200		
5	**SU NPP**	On-site NFC	MNUP BN-1200	Direct synthesis	Pyro
			MNUP BR-1200		
6			MNUP BN-1200	CTS	Combined
			MNUP BR-1200		
7	**GHK**	Centralized NFC	MOX BN-1200	MOX fuel	Hydro

When considering the site of SCC JSC, it was decided to consider a possibility of not only location on the Pilot Power Complex, but also to evaluate the option of placing production on the site of the NKP.

A significant difference of the SU NPP site is that the IEC competitive ability analysis is

An analysis of the cost of providing raw materials and components, chemicals and auxiliary materials, containers, energy, labor protection costs, depreciation of buildings and structures, equipment, vehicles, maintenance and operation costs, repairs and maintenance of buildings and other expenses was performed when accessing the feasibility of locating the production facility on the sites.

The results of the analysis are shown in figure 9.

IOP Conf. Series: Journal of Physics: Conf. Series **1475** (2020) 012007 doi:10.1088/1742-6596/1475/1/012007

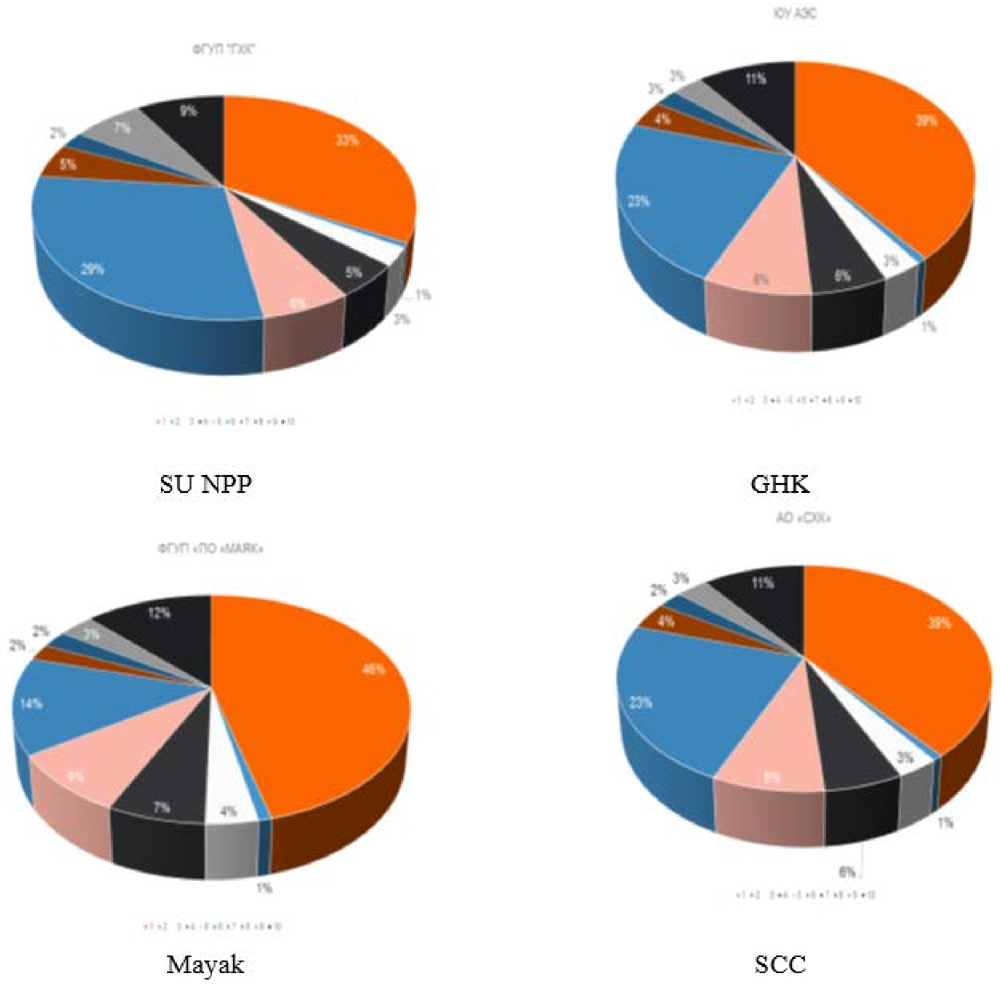


Figure 9. Analysis of costs for construction and operation of CNFC facilities on sites.

3. Conclusion

The following was carried out to develop the general design:

- development of design solutions to create unified process lines for the manufacture of uranium-plutonium nuclear fuel for BN-1200 and BR-1200 reactors;
- development of process and design solutions for reprocessing of spent uranium-plutonium fuel according to hydrometallurgical, pyrochemical, and combined technologies;
- development of process and design solutions to optimize the number of facilities for handling radioactive waste;
- development of design solutions for the Industrial Power Complex with CNFC general design consisting of closed fuel cycle production buildings and facilities.

The possibility of creating universal nuclear fuel production has been shown and the ways to unify processes lines have been proposed.

A synergistic effect is shown when joining pyrochemical and hydrometallurgical technologies into a combined one.

An integral assessment of operating costs of CNFC facilities at various sites has shown the close rates.

As a result of the general design, the advantages of the applied approach have been demonstrated and ways for further optimization have been shown.

IOP Conf. Series: Journal of Physics: Conf. Series **1475** (2020) 012007 doi:10.1088/1742-6596/1475/1/012007

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