ANNEX XII.

MODELLING OF REGIONAL COLLABORATIVE DEPLOYMENT SCENARIOS AIMED AT SOLVING THE PROBLEM OF SPENT NUCLEAR FUEL INVENTORY ACCUMULATION

XII-1. INTRODUCTION

Deployment of nuclear power is likely to be accompanied by the growth of global and regional nuclear fuel cycle (NFC) services markets and enhancement of the multinational and multilateral cooperation. A mature market already exists at the front end of the NFC, which enables a country to start or expand a national nuclear power programme without development and construction of front-end elements of the nuclear energy infrastructure. The NFC services can be provided by technology holder countries or from an international NFC centers. Examples of successful implementation of the multilateral approach in the NFC back end have already been demonstrated, although there is a still long way to go and obstacles to overcome in order to reach industrial, public and political consensus in the area. However, in order to provide timely answers to global challenges in nuclear power, modelling and analysis of regional architecture based on the multinational/multilateral approach to the backend of the NFC should be continued and intensified [XII-1]. These activities form an important task within the Terms of Reference of the SYNERGIES CP.

Countries-participants in the SYNERGIES CP represent different levels of nuclear power development and include nuclear energy technology holders, technology users and newcomers. Within the framework of CP SYNERGIES, Armenia, Belarus, Russian Federation, and Ukraine have considered a scenario of regional cooperation in the NFC back end. The considered model scenario can serve as a hypothetical example of potential interactions in NFC front and back end, since it involves nuclear energy countries with different programmes of nuclear power development and deployment.

According to definition proposed in the Final Report of the INPRO Collaborative Project on Global Architectures of Innovative Nuclear Energy Systems with Thermal and Fast Reactors and a Closed NFC (GAINS) for the use of the heterogeneous model which can depict a nuclear energy system (NES) consisting of countries with various level of nuclear technologies development, Armenia, Belarus, Russian Federation, and Ukraine belong to different strategy groups. Russian Federation belongs to the nuclear energy group which pursues a general strategy to recycle SNF (NG1). This group plans to build, operate and manage used fuel recycling facilities and permanent geologic disposal facilities for highly radioactive waste. Ukraine belongs to a nuclear energy group two – NG2 – which either follows a strategy of SNF direct disposal or of its reprocessing abroad. This group plans to build, operate, and manage permanent geologic disposal facilities for highly radioactive waste (in the form of used fuel and/or reprocessed waste) and/or to work in a synergetic way with another group to have its fuel recycled. Armenia and Belarus either have a general strategy to use fresh fuel supplied from abroad and to send spent fuel abroad for recycling or disposal, or the back-end strategy is still undecided (NG3). The simulation models of energy systems of these countries were based on possible regional activities in short term and did not reflect any specific national plans or programmes. This section presents the results of mathematical modelling and analysis of possible initial phase of regional cooperation at the back end of NFC and its drivers and impediments, as an outlook from the Russian Federation.

Russian Federation is an active participant in the regional and global multilateral cooperation and has plans for expansion of its activities. More than 10 nuclear power units are under construction abroad, construction of 20 new blocks are in negotiations. Russia is an established supplier of services at front-end of the NFC. The State Corporation "Rosatom" provides 8% of uranium mined worldwide, 17% of fresh nuclear fuels production, 22% of uranium conversion services, and 40% of enrichment services. In 2007 after the initiative of Russia the International Uranium Enrichment Center – (ICUE) was founded in Angarsk, Siberia under the guidance of the IAEA. Russia also has a certain experience in the fuel take-back option implementation where the leased fuel, once removed from the reactor and cooled down, was returned to the country of origin. Russian Federation NFC services are expected to be expanded under appropriate political and economic conditions. It was assumed in the study that International Fuel Cycle Centre (IFCC) could also be established in Russia as a part of international system of NFC services.

Ukraine has considerable experience in the use and development of nuclear energy technologies at the initial stage of the NFC: mining, conversion, fabrication of fresh fuel; however it is not planning to introduce the fuel recycling technologies in the near future. At the back end, long term storage of spent nuclear fuel (SNF) are considered to be main options. Reprocessing of SNF abroad is being considered by Russia to be an alternative option to the temporary storage.

Armenia plans to commission one VVER-1000 unit and assesses implementation of open fuel cycle or sending SNF to Russia for recycling. Belarus is building two VVER-1000 units and considers sending SNF to Russia for reprocessing and recycling to be the main back end option.

XII-2. REGIONAL MODEL AND SIMULATION TOOLS

Material flows within the regional model were simulated using computer codes MESSAGE [XII-2] and CYCLE [XII-3]. Spent fuel flows to Russia from abroad were simulated in a regional synergistic model based on multilateral approach. Meanwhile, a non-synergistic (national) model was used to compare effectiveness of multilateral and national approaches.

Figure XII-1 shows the simplified scheme of material flows in a regional synergistic model.

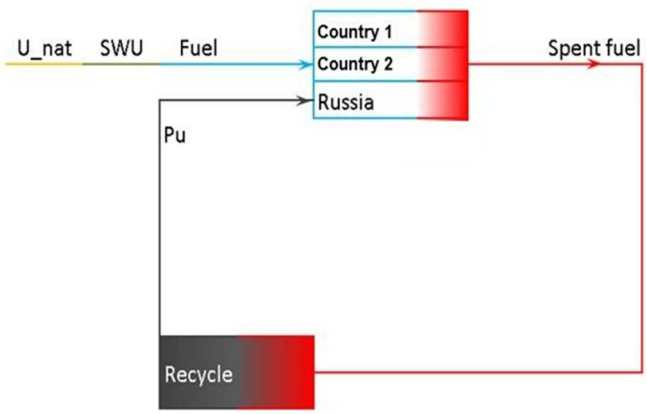

FIG. XII-1. Diagram of the regional synergistic model based on thermal and fast reactors and closed fuel cycle.

The system included the main elements of the NFC: mining of natural uranium, conversion, enrichment, fuel fabrication, fuel irradiation and electricity generation at nuclear power plants, cooling of SNF in reactor and interim storage, reprocessing, fabrication. The following types of reactors were considered in the system:

- VVER-440;
- VVER-1000;
- AVVER – advanced VVER;
- RBMK;
- SFR (BR=1.23).

The plutonium extracted from the fuel of thermal reactors VVER-440, VVER and AVVER and from the fast reactors is assumed to be re-used. Other separated products (uranium, minor actinides and fission products) are assumed to be kept in the storage facilities and to be further used or disposed of. RBMK SNF is assumed not to be reprocessed and to be kept in the temporary storage.

The following assumptions were adopted in order to calculate the material flows in the model:

- the range of forecasting was limited by year 2080;
- the modelling horizon was extended to 100 years to take into account edge effects with linear interpolation on the total installed capacity;
- the simulation step duration was taken for one year;
- nuclear power capacities were input in a continuous manner.

The optimization code MESSAGE distributed by the IAEA was applied to analyze the flows of nuclear materials and make economic assessment. MESSAGE (Model for Energy Supply System Alternatives and their General Environmental impacts) is a large-scale dynamic simulation code that is used for development of medium- and long-term energy scenarios and policy analysis. Basically, the scheme shown in Fig. XII-1 cannot be modelled with the use of the MESSAGE code as it needs “input-output” data for each reactor and NFC stage, which are not available without detailed physical calculations of the processes occurring in the reactor cores and decay of isotopes in the fuel cycle chains. However, application of the MESSAGE code can provide acceptable results of simulation of similar scenarios group on condition that the input data for MESSAGE is corrected with the use of a precise code.

The code CYCLE was developed in the Institute for Physics and Power Engineering (IPPE) as a precise code to simulate nuclide inventory evolution in reactors, storage facilities and other components of NFC. Data from this tool was inserted into to the MESSAGE user interface to provide higher reliability of the simulation results.

XII-3. SCENARIO ON THE VVER-FR COLLABORATIVE DEPLOYMENT AIMED AT SPENT FUEL INVENTORY ACCUMULATION PROBLEM SOLUTION

Scenario C.3 developed in CP SYNERGIES assumes collaboration aimed at solving the problem of accumulating spent fuel inventory among the countries that use LWR reactors of VVER type and FR reactors. Ukraine has a fleet of VVER reactors which operate in a once-through fuel cycle resulting in accumulation of SNF and plutonium while Russia is implementing a programme of BN type fast reactors deployment that needs plutonium for

initial loading of these reactors. This section provides an outlook of Russian participants of CP SYNERGIES on drivers and impediments in the initial phase of possible regional cooperation at the back end of NFC.

A variant of Russian NES arrangement which corresponds to federal programmes under development is presented in Fig. XII-2.

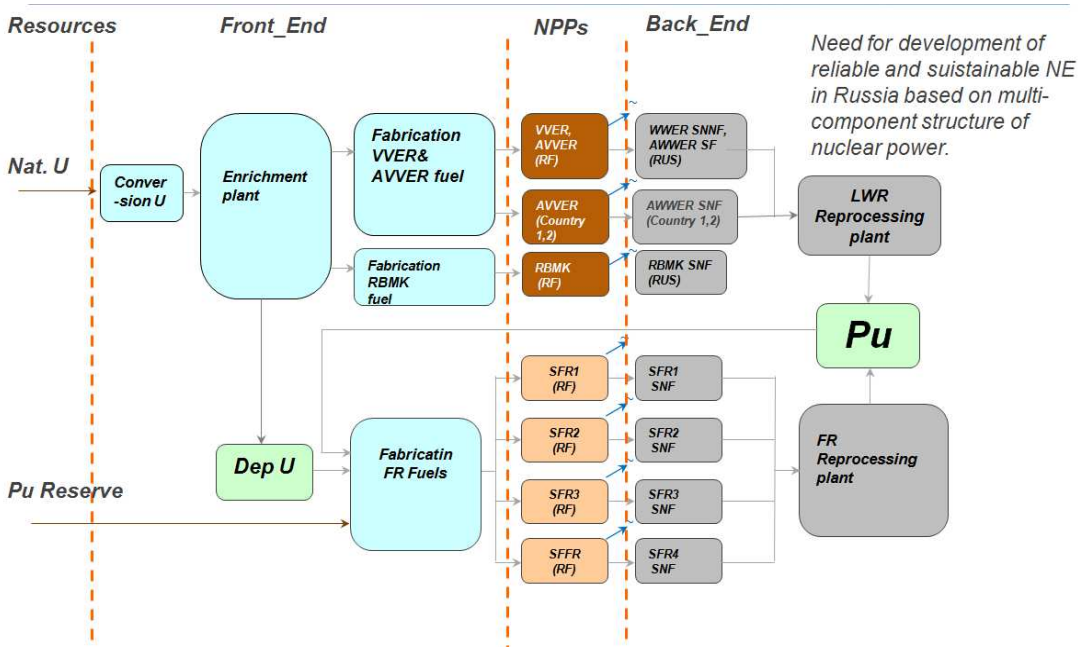

FIG. XII-2. A variant of Russian NES arrangement with correspondence to the Federal programmes under development.

The Ukraine SYNERGIES team provided a comprehensive report to the IAEA on the current state and prospects of nuclear power development in the country. According to the tasks of the study presented in this section, the front end and electricity generation of the Ukraine's NES were considered under "a black box" approach in which output of SNF will be reprocessed. Plans and programmes for construction of new NPPs in Armenia and Belarus were also presented to the IAEA (Figures XII-3 and XII-4).

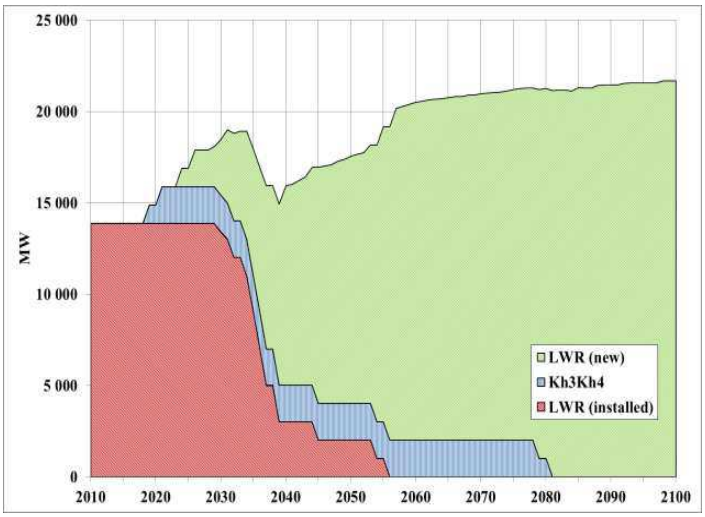

FIG. XII- 3. A variant for NPP commissioning in Ukraine.

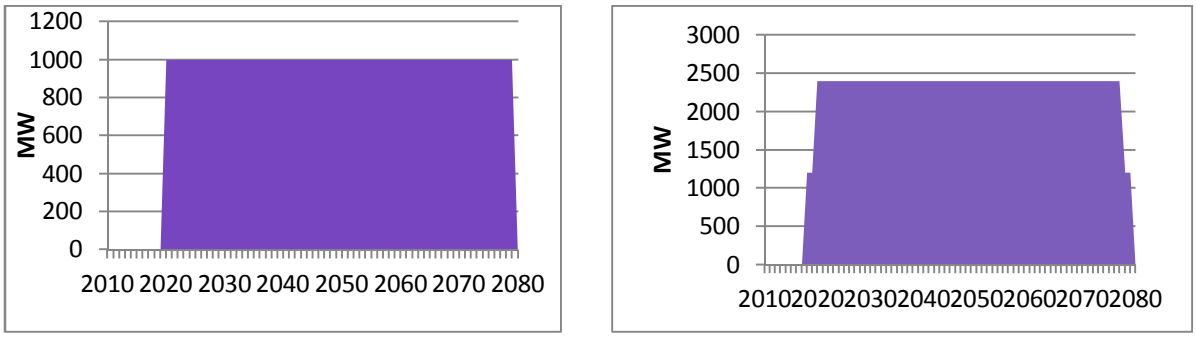

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FIG. XII- 4. Variants for NPP commissioning in Armenia and Belarus.

The study assumed that at the initial phase of regional collaboration which would last approximately till the middle of the century, possible SNF for recycling flows from abroad to the country where IFCC is supposed to be located will fall within the range of 150-400 t/year. Taking into account internal national studies, participants of the project agreed to consider the amount of SNF sent to IFCC as function of the rate of the national NPP deployment which, in turn, depends on overnight cost per kW(e) of NPP construction. $3000 per kW(e) was considered the minimum cost of NPP construction wherein nuclear power is more competitive and more SNF could be sent for reprocessing abroad. $5500 per kW(e) was considered a high cost of NPP construction when less SNF could be sent for reprocessing abroad.

XII-4. SCENARIOS AND CASES FOR SIMULATION OF REGIONAL COLLABORATION

As noted above, Russia belongs to GAINS nuclear strategy group NG1 where IFCC could be established. Nuclear power remains an important part of the Russian Strategy in the energy sector development up to 2030 (Table XII-1) [XII-4]. One of the strategy goals is to decrease the high share (68%) of the fossil fuel power plants.

TABLE XII-1. STRATEGY OF THE RUSSIAN ENERGY SECTOR DEVELOPMENT UP TO 2030. [XII-4]

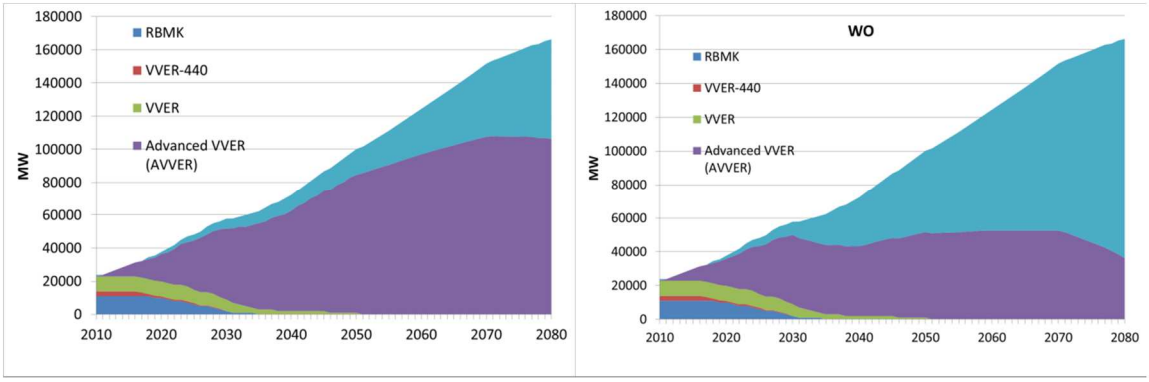
	Years				
	2005 (fact)	2008 (fact)	2013-2015	2020-2022	2030
Installed power plants' capacity, MW(e)	216.3	224.9	239-267	275-315	355-445
NPPs' capacity, MW(e)	23.7	23.8	28-33	37-41	52-62
Share of NPPs' capacity,%	10.9	10.6	12	13	14

The Strategy referred to in the Table XII-1 was developed in the period of the country's economic recovery. Nowadays the strategy is being revised. With economic development slowed down, the planned rate of energy capacities commissioning will be probably reduced. Nevertheless, a mutually beneficial 'win-win' collaboration with other countries in the area of nuclear energy is one of the priorities of the state policy and a driver for the national industry.

Closure of the NFC in the two-component NES based on thermal and fast reactors is included into the short term agenda.

In this context, two variants of the Russian two-component nuclear power structure were developed, see Fig. XII-5:

- NES with sodium fast reactors (SFR) share of 15% by 2050 and 50% by 2100 (to be referred to as low share of SFR);
- NES with SFR share defined by available plutonium for these reactors loadings (to be referred to as high share of SFR).



a b

FIG. XII-5. The structure of the Russian nuclear power industry with low (a) and high (b) shares of fast reactors.

The input data on VVER-1000 necessary for the cases simulation was taken from the database developed in CP GAINS [XII-1] and extended by the IAEA's INPRO Section. Russian fleet of fast reactors was assumed to consist of BN-1200 reactors. Some characteristics of the BN-1200 are presented in Table XII-2 [XII-5].

TABLE XII-2. SOME TECHNICAL CHARACTERISTICS OF BN-1200 FAST REACTOR.

Parameter	Data
Capacity (thermal)	2900 MWt
Capacity (electrical)	1220 MW(e)
Coolant	Sodium
Core loading	46.9 t HM
Mass share of Pu in fuel	18.1%
Fuel campaign	4-6 years
Refuelling time	1.0 year
Breeding ratio (BR)	1.2
Storage before reprocessing	3.0 years

Three cases were considered within each variant:

- a non-synergistic case in which the Russian Federation reprocesses only SNF from NPPs located in the Russian Federation, while SNF from NPPs in Ukraine accumulate at local SNF storage facilities;
- synergistic case 1: SNF from NPPs located in Russia and Ukraine is reprocessed at Russian reprocessing plants; the amount of the VVER SNF sent to Russia from

Ukraine corresponds to the higher level of supply noted in the Fig. XII-3 as dSF3000;

- synergistic case 2: SNF from NPPs located in Russia and Ukraine are reprocessed at Russian reprocessing plants; the amount of VVER SNF sent to Russia from Ukraine corresponds to lower level of supply shown in the Fig. XII-3 as dSF5500.

For each case the following indicators were calculated:

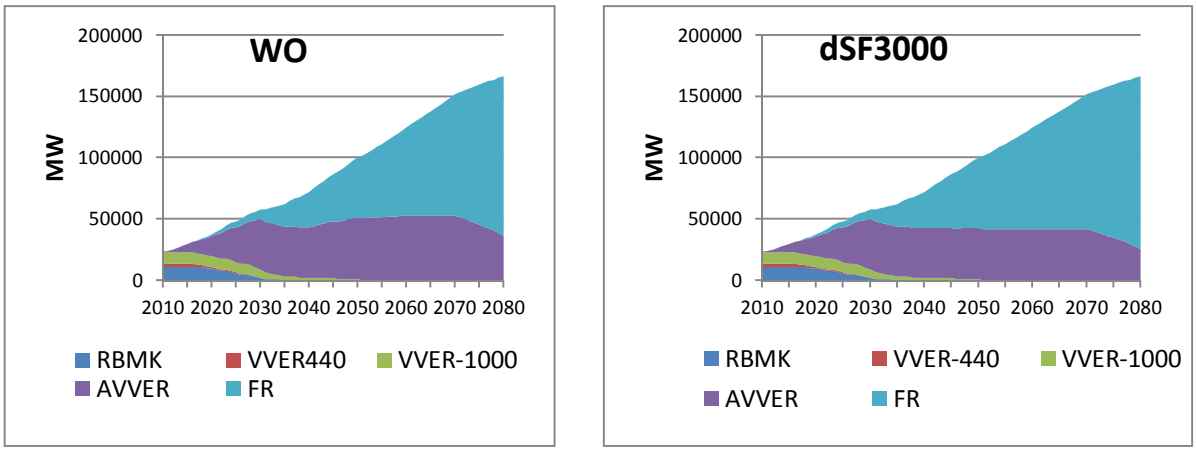
- structure of nuclear power generating capacities;
- cumulative consumption of natural uranium;
- separation works;
- rate of fuel production;
- amount of SNF at storage;
- rate of SNF reprocessing;
- plutonium balance at storage facilities;
- natural uranium prices for the cases of high and low FR shares.

Results of calculation and analysis performed for some of these indicators are discussed below.

XII-5. ANALYSIS OF CERTAIN INDICATORS FOR THE SIMULATED SCENARIO

XII-5.1. Structure of nuclear power generating capacities

The structure of the Russian nuclear power generating capacities calculated for the variant with the share of SFR defined by available plutonium from VVER is shown in Fig. XII-6. The calculations of the indicators were performed for two cases: the non-synergistic case where only SNF from NPPs located in Russia is reprocessed and the synergistic case 1 where SNF from NPPs located in Russia and Ukraine is be reprocessed.



a b

FIG. XII-6. The structure of the Russian nuclear power industry in non-synergistic case (a) and synergistic case (b) for the variant of high share of fast reactors.

The non-synergistic case is noted in Fig. XII-6(a) as WO, the synergistic case 1 is noted in Fig. XII-5(b) as dSF3000. It can be seen that addition of the Ukrainian SNF to the amounts assumed does not change the structure of the Russian nuclear power significantly. The impact

on the Russian nuclear power sector structure of transition from synergistic case 1 to synergistic case 2 is even less. The share of SFR in all three cases is shown in Fig. XII-7.

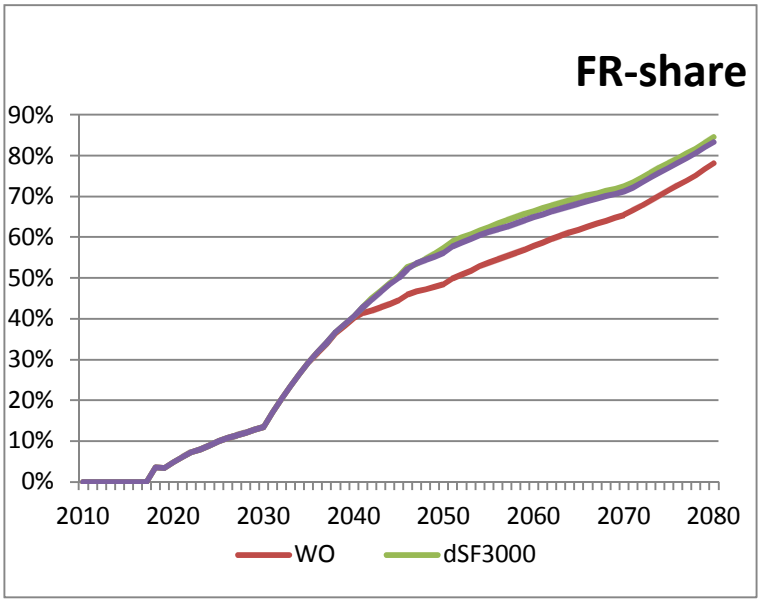


FIG. XII-7. The share of SFR in synergistic and non-synergistic cases for the variant defined by available plutonium for these reactors loadings.

This graph demonstrates that, within assumptions accepted, the maximum growth of SFR share in Russian nuclear power sector to provide a balance of plutonium generation and consumption for synergistic cases equals approximately 10%.

XII-5.2. Natural uranium demand for the case of high fast reactors share

Natural uranium demand for the non-synergistic case based on Russian national program of nuclear power deployment is shown in Fig. XII-8(a). Figure XII-8(b) demonstrates demand for natural uranium in the synergistic case where the SNF from VVERs located in the regional group is reprocessed, while plutonium extracted from this SNF is fully recycled into the fuel for BN-1200 and therefore is providing high share of fast reactors in the structure of the Russian nuclear power generating capacities.

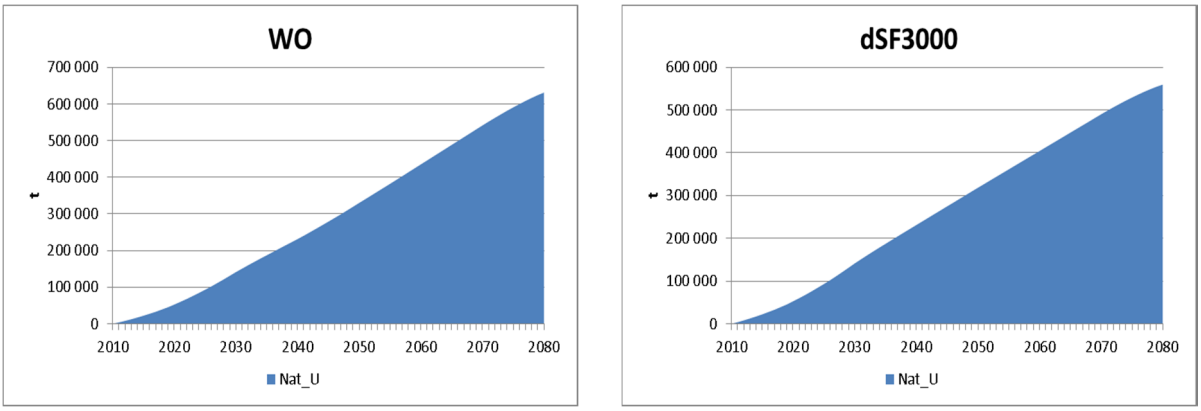


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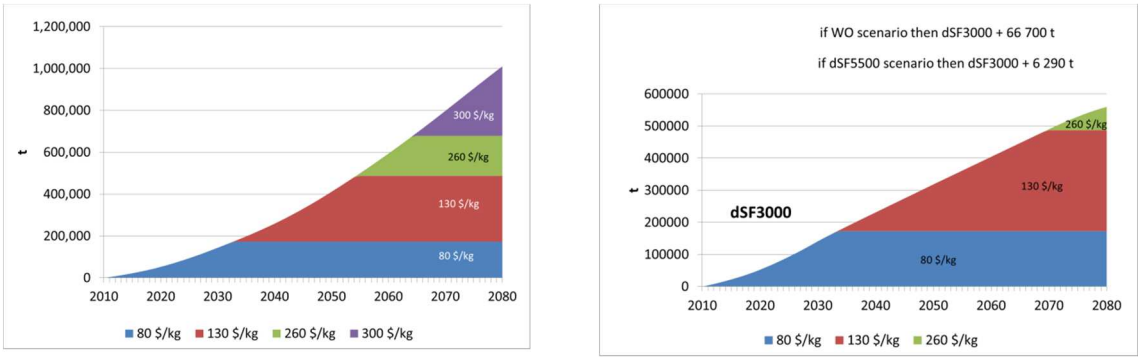
FIG. XII- 8. Natural uranium demand for the non-synergistic (a) and synergistic cases (b) for the variant of high share of fast reactors in Russia as NG1 country.

It can be seen in Fig. XII-7 that the synergistic case slightly reduces natural U consumption (~50 thousand tons) due to the use of additional plutonium in MOX fuel instead of UOX. No perceptible impact on the natural uranium price was identified for these two cases. However, change in nuclear power generating capacities structure in the recipient country can impact the natural uranium prices rather significantly.

XII-5.3. Natural uranium prices for the cases of high and low fast reactors share

Natural uranium demand in the case of low fast reactors share in the structure of the Russian nuclear power capacities, see Fig. XII-6(a), is about 1 million tons, which is much higher than ~550 thousand tons in the case of high fast reactor share, see Fig. XII-6(b). The increase in natural uranium consumption is bound to result in uranium prices increase, see Fig. XII-9.

As shown in Fig. XII-8, in the case of high fast reactor share in the recipient country the partners of regional cooperation can benefit from the use of cheap natural uranium (80-130 $/kg) because of the utilization of more plutonium in fuels, whereas they can exhaust cheap uranium deposits and will have to buy more expensive uranium (260-300 $/kg) in the case of low fast reactor share.

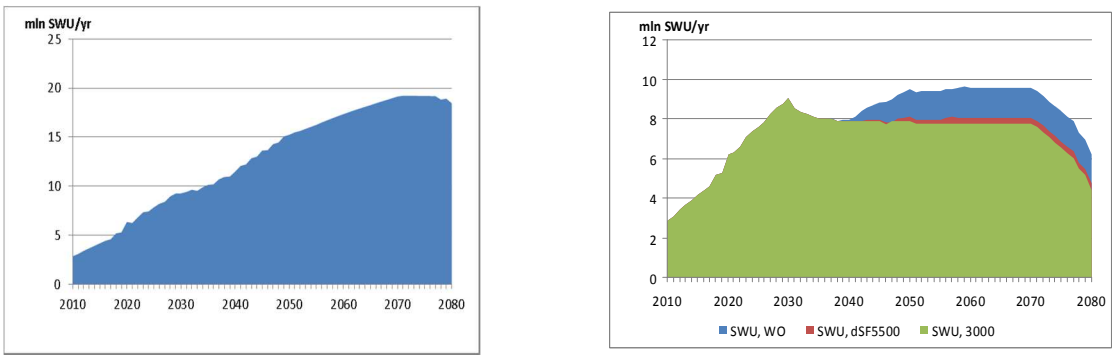


a b

FIG. XII-9. Natural uranium prices for the low (a) and high (b) fast reactor shares in the structure of the Russian nuclear power capacities

XII-5.4. Demand for enrichment services

Figure XII-9 below illustrates the demand for enrichment services for cases examined in the study.



a b

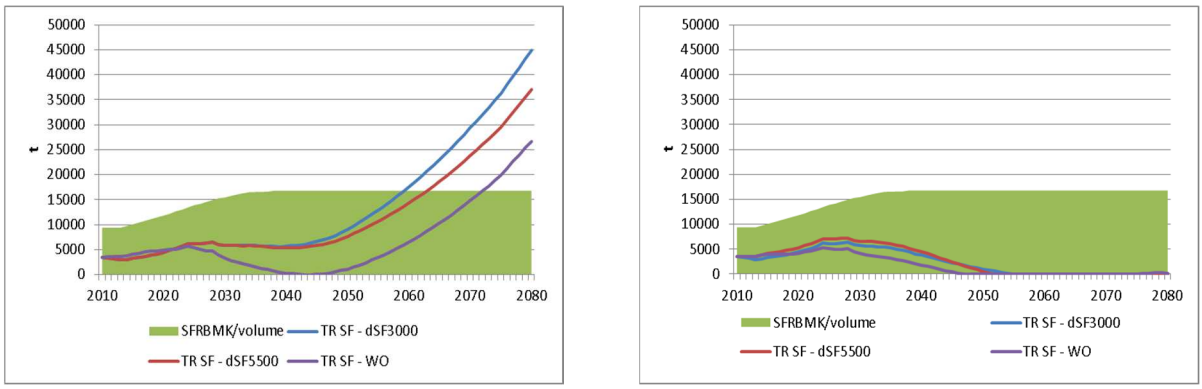
FIG. XII-9. Demand for enrichment services for the variants of Russian nuclear power industry structure with low (a) and high (b) share of fast reactors.

Figures XII-9, a and XII-9, b represent demand for enrichment services for the variants of Russian nuclear power structure with low and high share of fast reactors, respectively. An expected effect of demand reduction for enrichment services during transition to enhanced reprocessing is observed. As it can be seen from Fig. XII-9(b), regional cooperation would add up to the reduction effect in enrichment services, but not significantly.

XII-5.5. Management of SNF and plutonium

Figure XII-10 demonstrates that accumulation of SNF in the country which receives this fuel from abroad is very sensitive to the ratio of thermal and fast reactors in its NES. There is a trend to accumulate of SNF in the storages of Russian reprocessing facilities in the variant with low share of fast reactors, see Fig. XII-10(a). The contribution of SNF supply from abroad in this variant is rather perceptible.

In the variant with high share of fast reactors, plutonium from SNF of Russian and Ukrainian VVERs could be reused by 2050, see Fig. XII-10(b). As mentioned above, at present there are no plans in Russia to reprocess SNF from RBMK reactors.



a b

FIG. XII-10. SNF accumulation in the Russian storage facilities for low (a) and high (b) share of fast reactors.

As shown in Fig. XII-11, in the variant with high share of fast reactors plutonium from storage can be used before all SNF is reprocessed. This means that after separation plutonium has to be directed to the fuel fabrication without any delay.

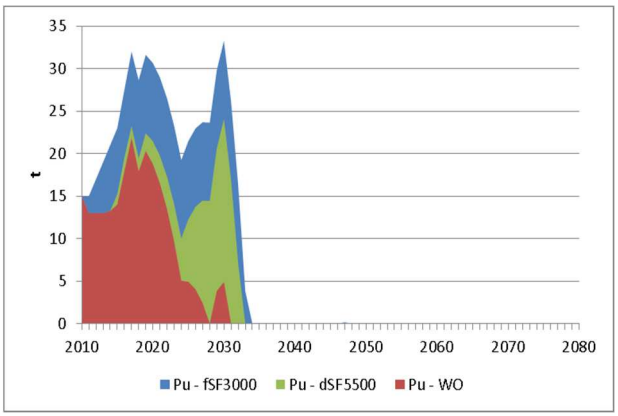


FIG. XII-11. Plutonium accumulation in the variant of high share of fast reactors.

While demonstrating the potential of avoiding excessive accumulation of SNF and plutonium through regional collaboration, the study noted economic impediments to implementation of this option in the near prospect. At present, technical and institutional procedures are not developed in detail and the price formation in the area is not transparent. Long-term intermediate level waste (ILW) storage looks more attractive from economic point of view although it is connected with certain challenges in the long term.

XII-5.6. Load efficiency of VVER fuel reprocessing plants

Figure XII-12 illustrates that within the assumptions made the regional cooperation of Ukraine and Russia in the back end of NFC would not result in a significant impact on capacities of Russian VVER fuel reprocessing plants planned for commissioning in the national programme of closed NFC.

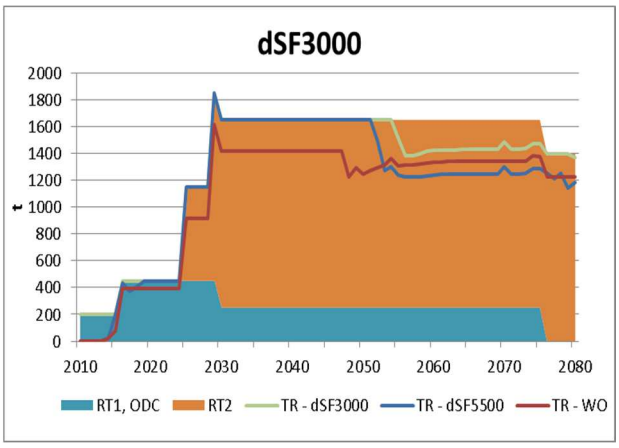


FIG. XII-12. Load efficiency of VVER fuel reprocessing plants for the variant of low share of fast reactors.

However, Figure XII-12 also demonstrates that reprocessing capacities in Russia completely match goals stated in the national programme and they do not have necessary capacity reserves for further expansion of regional collaboration.

XII-6. CONCLUSIONS

To date, only preliminary steps are underway to develop regional and global collaboration on the back end of the NFC. Within the SYNERGIES framework it was agreed to consider a scenario of regional cooperation of the countries that use VVER-type reactors, the technology held by the Russian Federation. Armenia, Ukraine and Russia have studied models for the possible initial stage of regional collaboration in order to demonstrate qualitatively and quantitatively the costs and benefits of such an approach. The analysis provided in this section briefly summarized results of the study as seen by the Russian SYNERGIES participants.

The enhancement of multilateral collaboration at the back end of the NFC appears to be inevitable solution on the path towards regionally/globally sustainable nuclear power. Some drivers and impediments in the specific example of regional cooperation on the NES based on the VVER type of thermal reactors and BN type of fast reactors were identified. Some of the drivers or impediments of the regional collaboration include:

- substantial savings of natural uranium for collaborating partners due to substitution of uranium-235 in UOX nuclear fuel of VVER by plutonium extracted from UOX SNF of VVER and used in MOX fuel of FR;
- opportunity to avoid excessive accumulation of SNF and plutonium through its collaborative management;
- economy of financial and manpower resources for users on the expansive infrastructure of the closed NFC together with benefiting from all its advantages;
- expansion of nuclear energy business for the technology holders and cost reduction of NFC services;
- the possibility to utilize cheaper categories of uranium for both users and technology holders.

Along with the drivers some impediments for the regional collaboration were identified:

- technical and institutional procedures are not developed in detail, the price formation in this area is not transparent and does not stimulate implementation of abroad reprocessing;
- political and economic instability may hamper multilateral collaboration.

Participants of the project have applied a comprehensive methodology, databases and tools established in the IAEA and INPRO for the scenario studies and recognize the need in their further development.

In particular, more adequate simulation of regional collaboration requires further research on a number of issues, such as:

- reducing the uncertainty of initial data on the cost of the fuel cycle elements, including transportation;
- development of the methodological basis of the estimation of the value of SNF reprocessing products (regenerated uranium, plutonium, etc.);
- clarification of SNF deliveries timing, storage times and conditions of reprocessing, the inventory of the returned materials, uncertainty of economic data, etc.

The main conclusions for the prospects of regional collaboration are convincing. Further research should consider scaled demonstration of the recycling technologies (LWR-MOX, FR-MOX) and their economics, including, among other things, the capital cost of BN versus VVER and the cost of fuel fabrication for BN versus VVER.

REFERENSE TO ANNEX XII

[XII-1] INTERNATIONAL ATOMIC ENERGY AGENCY, Framework for Assessing Dynamic Nuclear Energy Systems for Sustainability, Final Report of the INPRO Collaborative Project on Global Architectures of Innovative Nuclear Energy Systems with Thermal and Fast Reactors and a Closed Nuclear Fuel Cycle (GAINS), IAEA Nuclear Energy Series NP-T-1.14, Vienna (2013)

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