ANNEX XXI.

HOMOGENEOUS AND HETEROGENEOUS WORLD SCENARIOS WITH VVER-S, SMR AND HTR, INCLUDING NON-ELECTRICAL APPLICATIONS

XXI-1. INTRODUCTION

XXI-1.1. Natural uranium resources

Before the evaluation of nuclear power development scenarios sustainability, it is necessary to understand volume of available natural uranium resources. Some of the main sustainability limitations are natural uranium resources and cost of uranium production. Sustained development assumes not only power capacities growth but also supplying them with fuel during lifetime.

World conventional natural uranium resources are estimated approximately at 20 million tons, see Table XXI-1. Additionally, more than 20 million tons of uranium are considered to be present in unconventional uranium resources, such as phosphate rocks, non-ferrous ores, carbonatite, black shale and lignite [XXI-1].

TABLE XXI-2. URANIUM RESOURCES BY CATEGORIES

$/kgU	Identified resources		Undiscovered resources		Total
	Reasonably assured resources (RAR)	Inferred resources (IR)	Prognosticated resources	Speculative resources	
< 80	2 014 800	1 063 700	1 624 100	-	4 702 600
< 130	3 455 500	1 871 700	2 698 000	3 543 800	11 569 000
< 260/ unassigned	4 378 700	2 717 900	2 841 300	3 862 100/ 3 733 200	17 533 200

Large quantity of uranium is contained in seawater, about 4 billion tons, and the cost of extraction is assumed to be comparable to the cost of production from an ore which is currently about 250 $/kgU. However, this price does not take into account large volume of consumed materials, their production and utilization that may increase given estimations.

In the study the upper bound of affordable uranium resources was taken as 20 million tons up to 2100. If this value is exceeded, scenarios should be considered as non-complying with the principles of sustainable development (according to the basic economic principle "…affordable and available"). It should be noted that this is integral uranium reserve, and production of uranium will become harder and more expensive upon its exhaustion, i.e., it gradually becomes less economically available and may cause possible transition from the market to auction with unpredictable price changing. It should be noted that according to the IEA study "Energy technology perspectives" (2012) [XXI-2] it is suggested that only 6 million tons of natural uranium will be available and economically affordable for use in 2075 and, at the same time, fast reactors (FRs) will form a significant share in nuclear energy structure.

Figure XXI-1 shows natural uranium consumption by world nuclear energy capacities for open fuel cycle with installed capacity of 1500 GW in 2050.

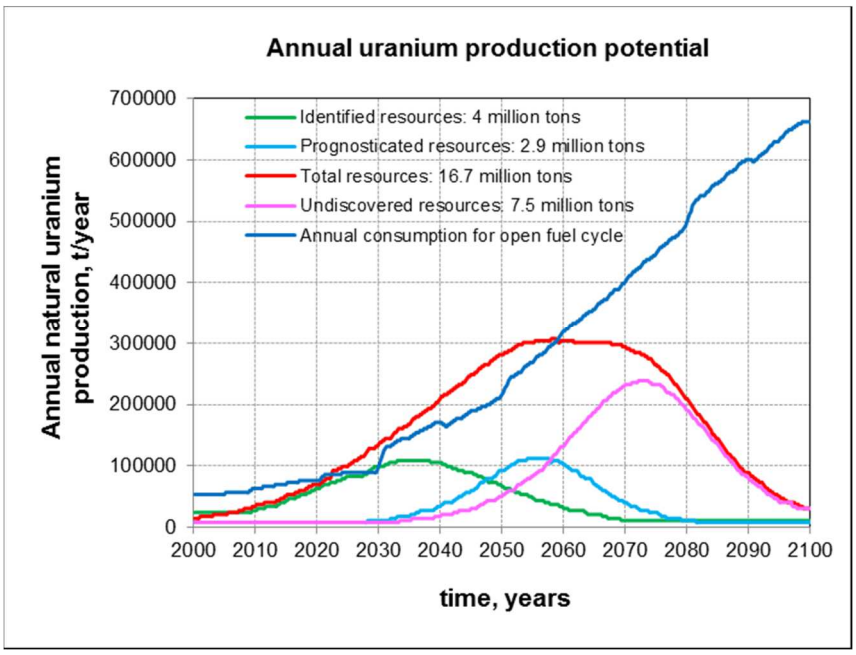


FIG. XXI-1. Assessment of annual uranium production potential.

Exploration of new resources may shift peak of annual production, but it will not solve the problem of resources exhaustion, therefore it is required to find an alternative to open fuel cycle with high power growth. At present time closed fuel cycle is considered in order to reduce uranium consumption and provide capacity growth.

The study provides analysis of open and closed fuel cycles for moderate and high scale nuclear power development scenarios for homogeneous and heterogeneous cases with VVER-S, SMR and HTR reactors. All calculations were performed with the help of DESAE 2.2 code.

XXI-1.2. DESAE 2.2 code description

The DESAE (Dynamic of Energy System Atomic Energy) code has been developed in NRC "Kurchatov institute" during the last ten years. It is used for system studies of nuclear power development prospects. It is necessary to consider full set of processes in nuclear power plants that ultimately lead to energy production. The purpose of analysis is definition of nuclear energy structure, time frames for innovative technologies deployment, of the main parameters of fuel cycle plants: mining capacities, enrichment and reprocessing plants, material balances, financial assessments of choosing scenarios, and assessment of environmental impact factors and risks. The code allows making calculations taking into account regional features of nuclear object location [XXI-3].

The general scheme of the DESAE mathematical model reflects the structure of nuclear energy system and its dynamics, including its fuel production and consumption components. Existing reactors of different types are considered, as well as innovative reactor technologies and fuel cycles. It is also possible to analyze electronuclear and fusion reactors, including hybrid fusion systems focused on additional fission isotopes breeding. Isotopic balance can be calculated taking into account closing of a nuclear fuel cycle and the most important parameters of fuel use.

The DESAE code allows carrying out calculations in an interactive mode, modify calculation process, quickly analyze variants, change power capacities structure and fuel cycles in order to choose a scenario.

In the first stage, a user forms a task for calculation including information on the set of selected reactors, their power capacities, reprocessing plants, rate of growth and scale of different plants, etc.

In the second stage, a specified variant is calculated. Calculation time is approximately 1 minute, which increases work efficiency.

In the third stage, the information is drawn on screen and the results are processed. If necessary, data may be transmitted to Excel for easier processing.

Key elements of the interactive code DESAE focus on nuclear energy dynamics description and the reflected substantial information about the system under study is shown in Fig. XXI-2.

This fuel cycle structure is realized in the code and used in both, regional and global calculations. Regional features are reflected in input data defining power capacity of NPPs, their types, power capacity of reprocessing plants, etc.

Reactor characteristics are defined as time dependencies, which allows considering possible modifications of characteristics during reactor lifetime. Other factors may also be considered, such as fuel loading parameters dynamics, spent nuclear fuel (SNF) storage time, thermal efficiency, etc.

Calculated data includes all significant parameters and is sufficient for scenario analysis and expert assessment preparation.

The DESAE code was developed in the framework of the IAEA's INPRO project [XXI-4 and XXI-5]. It was verified and there is already significant experience of its application. It is used for research of nuclear energy systems carried out by different Russian and foreign researchers.

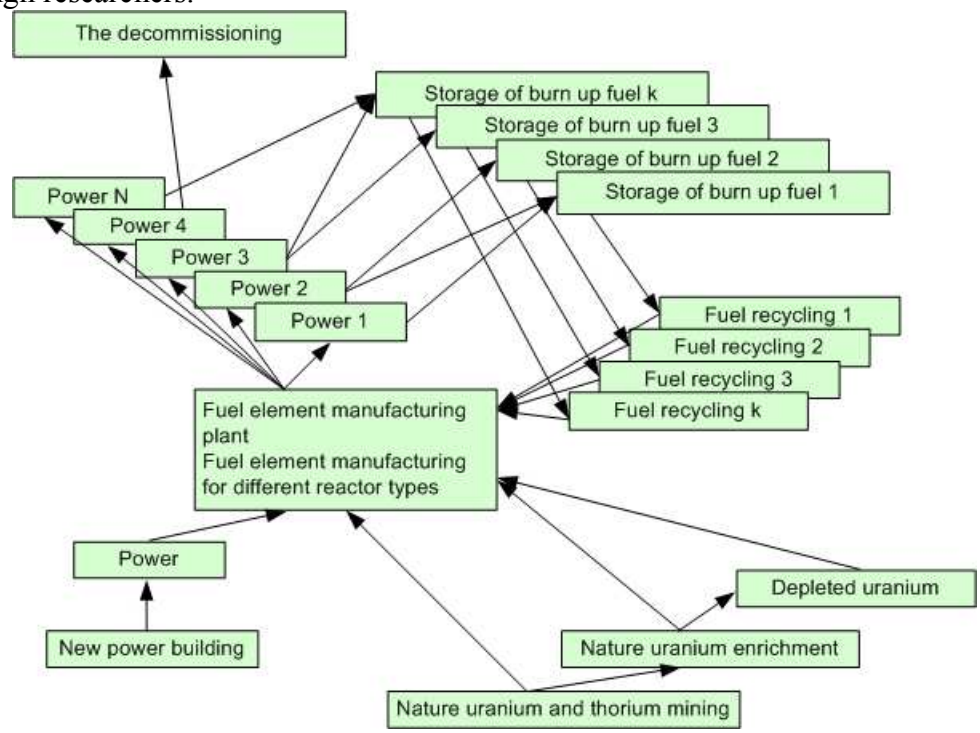


FIG. XXI-2. Key elements of fuel cycle in mathematical model of the DESAE code.

XXI-2. MODELLING RESULTS FOR MODERATE AND HIGH CASE OF OPEN FUEL CYCLE

In this sub-section the results are analyzed for moderate and high cases of power capacity for the basic structure of nuclear energy and with VVER-S. These cases are analyzed in global consideration, i.e., the world is assumed to be a homogeneous system and all countries may exchange resources and technologies in necessary volume.

XXI-2.1. Moderate case

Variant with open fuel cycle and thermal reactors is considered as a basic scenario. LWR and HWR reactors continue work from 1970, and in 2015 ALWR start to be deployed. ALWR reactor designs, such as APWR, EPR, ABWR, etc., are licensed, and several are currently under construction or planned to be built in the nearest time. Structure of the basic scenario is shown in Fig. XXI -3. Ratio between ALWR and HWR is 94% and 6%, accordingly.

Due to reactors development, the next generation of reactors is considered which is called VVER-S. This reactor is developed to optimize work of LWR in a closed fuel cycle: it can work with mixed oxide (MOX) fuel and has high breeding ratio. Also super-critical water parameters allow reaching high thermal efficiency of approximately 43-45%.

A lot of work has already been done for this project and 20 years have been accumulated of R&D experience and experiments with water of super-critical parameters. However, certain important questions require additional studies: structural materials, their corrosion, thermal-hydraulic resistance issue, etc. [XXI-6].

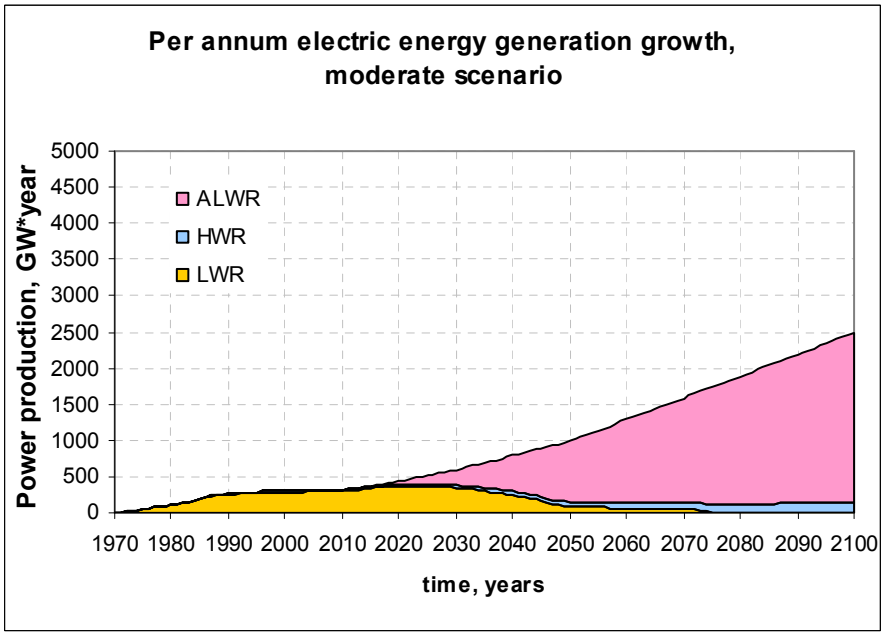


FIG. XXI -3. Power production (moderate scenario).

Table XXI-2 shows main characteristics of VVER-S reactor.

TABLE XXI-2. MAIN SPECIFICATIONS OF VVER-SUPER (VVER-S)

Reactor specification	Value
Reactor net electric output, MW	1330
Reactor thermal output, MW	3300
Thermal efficiency, %	40.3
Average load factor, %	85
Operation cycle length, effective full power days (EFPD)	335
Number of refuelling batches	4
Fuel residence time, EFPD	1340
Enrichment, %	4.9
Specific power density, MW/t	45.2
Average discharge burn-up, MWday/t	60 000
Initial core inventory, tHM	73
Equilibrium loading , tHM/a	18.250

Isotopic composition of VVER-S reactor fuel used for calculation can be found in Appendix I to this Annex.

In view of the problems described above it is expected that this type of reactor may be deployed in 2025, and at the same time from then on no more reactors of third generation will be deployed.

The ratio of power capacity between VVER-S and HWR is 94% and 6 %, similar to the basic variant, see Fig. XXI45.

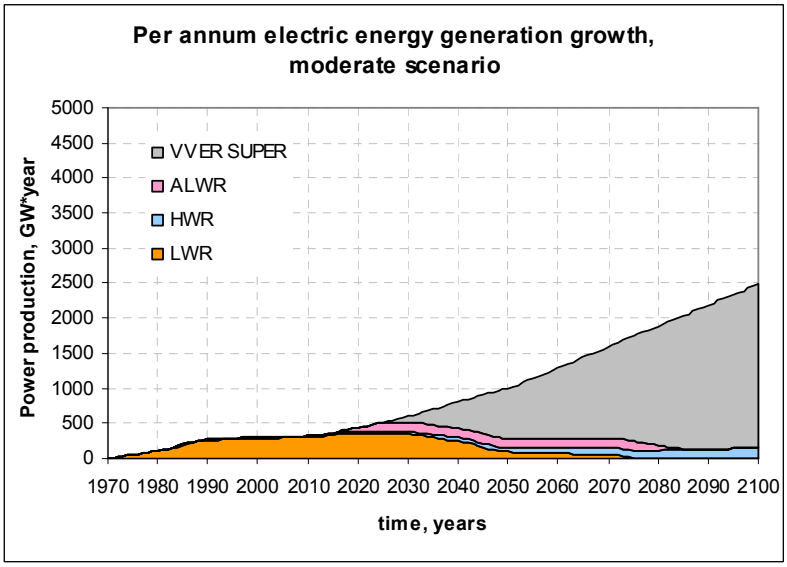


FIG. XXI-4. Power production with VVER-S (moderate scenario).

VVER-S reactors are noted for effective fuel use that allows reduction of annual and cumulative natural uranium consumption in comparison with the basic variant. This saving will constitute about 13 % in 2100 for moderate case and it will allow working within the frame of the accepted limitations of uranium resources (Fig. XXI-5).

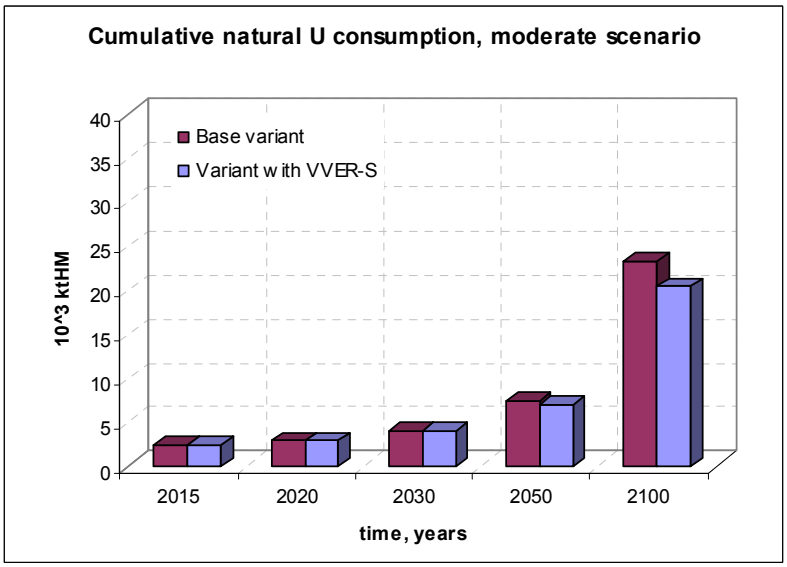


FIG. XXI-5. Cumulative natural U consumption – moderate scenario.

Reduction of uranium consumption will obviously require less power capacities of separation facilities, reduce the volume of depleted uranium, etc.

At the same time, there is the problem of SNF accumulation in long-term storages or be sent for disposal in the case of an open fuel cycle. Figure XXI-6 shows SNF amount for moderate case for both, basic and VVER-S variants.

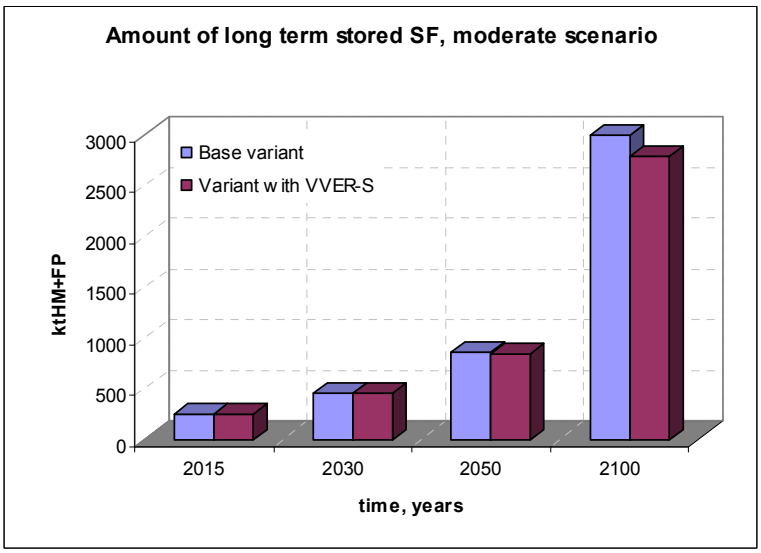


FIG. XXI-6. Amount of long term stored SNF – moderate scenario.

The largest part of the generated SNF is that of HWR and VVER-S reactors. It should be noted that the share of HWR reactors is substantially smaller than the share of VVER-S. Apart from the volume of SNF, its important parameters also include radioactivity and decay heat. Decay heat for HWR's SNF will be significantly less than for light water reactors' SNF. It should be noted that VVER-S reactors are intended mainly for work in a closed fuel cycle; in this, there are no problems with SNF reprocessing and final disposal associated with the increase of minor actinides content and decay heat.

XXI-2.2. High case

In this study high cases are scenarios with power growth up to 5000 GW by 2100. Figure XXI-7 shows the basic variant, i.e., the variant with current reactor technologies used.

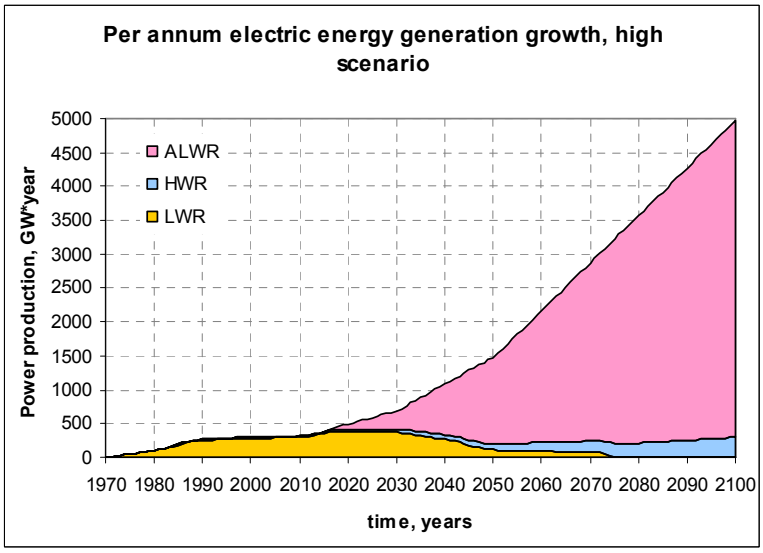


FIG. XXI- 7. Power production (high scenario).

However, LWR of next generation will presumably be built in the medium-term future. These reactors have enhanced safety characteristics and higher effectiveness of fuel use. Nuclear energy system with VVER-S reactors is shown in Fig. XXI-8.

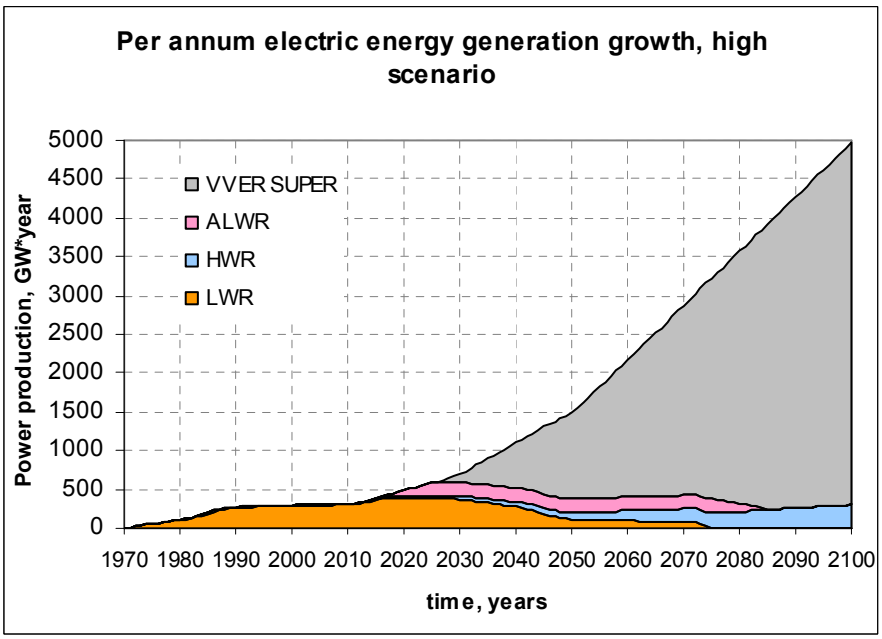


FIG. XXI- 8. Power production with VVER-S (high scenario).

Annual uranium consumption may possibly be reduced to 130-135 t/year due to new solutions implemented in super-critical reactor. Figure XXI-9 presents a comparison of the cumulative uranium consumption for the basic and VVER-S scenarios.

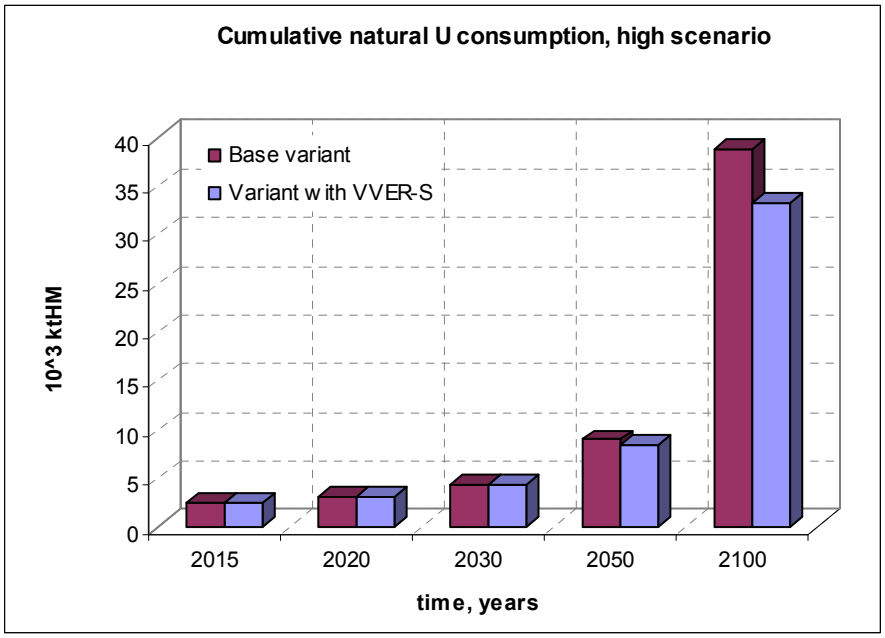


FIG. XXI-9. Cumulative natural U consumption – high scenario.

Savings of cumulative natural uranium consumption reach almost 15 % by the end of the century for high scenario with VVER-S. Nevertheless, despite its general reduction the uranium demand significantly exceeds the reserves under 260 $/kg price. No definite conclusion can be made about possibility of sustainable development within the frame of the accepted limitations.

It is obvious that nuclear power growth results in a growth of SNF volume. Figure XXI-10 shows comparison of SNF volume for different variants of open fuel cycle realization.

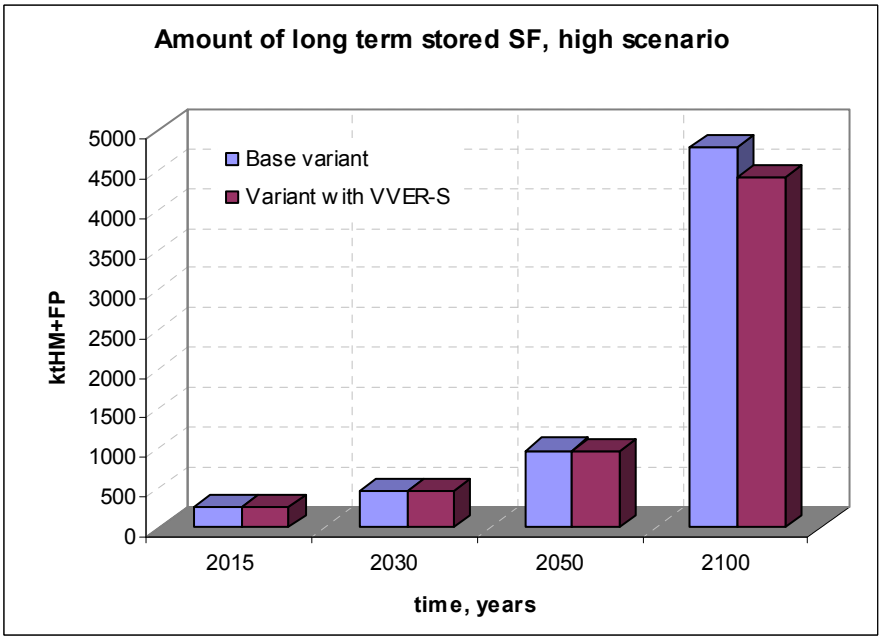


FIG. XXI-10. Amount of long term stored SNF – high scenario.

It should be noted that q twofold power growth leads to SNF volume increase by 60 % in comparison with the moderate case.

Calculation results for open fuel cycle scenarios with different generations of LWR are presented in Table XXI-3.

TABLE XXI-3. COMPARISON OF ANNUAL NATURAL URANIUM CONSUMPTION AND SWU FOR BASIC VARIANT AND VVER-S VARIANT (MODERATE AND HIGH SCENARIOS)

Annual natural uranium consumption, kt/year					
	2015	2020	2030	2050	2100
Moderate					
Basic	86	103	133	186	454
VVER-S	86	102	126	159	375
High					
Basic	95	115	154	282	904
VVER-S	95	114	145	239	746
Cumulative natural uranium consumption, million t.					
Moderate					
Basic	2.41	2.90	4.07	7.39	23.38
VVER-S	2.41	2.90	4.04	7.04	20.40
High					
Basic	2.44	2.99	4.32	8.92	38.87
VVER-S	2.44	2.98	4.28	8.35	33.24

TABLE XXI-3. COMPARISON OF ANNUAL NATURAL URANIUM CONSUMPTION AND SWU FOR BASE VARIANT AND VVER-S VARIANT (MODERATE AND HIGH SCENARIOS) (cont.)

Annual separating work demand. thousand SWU/year					
Moderate					
Basic	47	62	91	156	397
VVER-S	47	61	84	131	324
High					
Basic	52	71	107	237	792
VVER-S	52	70	99	199	645
Cumulative volume of SNF. ktSNF					
Moderate					
Basic	251	305	442	857	2987
VVER-S	251	305	442	847	2787
High					
Basic	251	306	457	976	4790
VVER-S	251	306	456	960	4422
SNF decay heat. million kW					
Moderate					
Basic	0.57	0.62	0.87	1.63	4.36
VVER-S	0.57	0.62	0.86	1.54	3.67
High					
Basic	0.57	0.64	0.97	2.21	8.39
VVER-S	0.57	0.64	0.96	2.06	7.08

XXI-2.3. Conclusions to section XXI-2

The analysis shows that VVER-S reactors are suitable for moderate case and allow more efficient use of natural uranium. However, exploitation of only innovative thermal reactors is not sufficient, and it is necessary to apply innovative technologies to the whole system. Effectiveness of innovative thermal reactors is manifested in the case of operation with effective breeders in a close fuel cycle. In the moderate case large volume of SNF is accumulated, and it is necessary to watch it during long time period. Besides, in the high case there is uranium resource shortage independent of the technology used.

XXI-3. MODELLING RESULTS FOR CLOSED FUEL CYCLE

It is possible to solve the problems of resources and large SNF volume accumulation in a closed NFC at high rate of nuclear energy development. The idea of VVER-S creation is based on nuclear energy development strategy that allows reaching maximum effectiveness of existing VVER reactors by adjusting them to requirements of nuclear energy systems with high breeding reactors. Thermal reactors do not solve problems of sustainable development in systems with fast reactors which have low breeding ratio. So, thermal reactors can be effective only in synergistic collaboration in an innovative nuclear power system that will allow sustainable development of both energy and resources. Present study considers involvement of ^{238}U by means of fast reactors (BR~1). Fast reactors are assumed to start operation in 2020 with fuel made from plutonium extracted from thermal reactors' SNF. All

SNF is assumed to be reprocessed after irradiation and storage. Fuel cycle length of reactor is three years.

All scenarios for closed fuel cycle are analyzed from both, global and regional perspective with non-synergistic and synergistic collaboration, which allows understanding a level of collaboration impact on fuel cycle structure, material balances, etc.

XXI-3.1. Group consideration

The strategy adopted is based on the GAINS heterogeneous world model [XXI-7] with three nuclear power producer groups of countries (NG1, NG2 and NG3) with different policy regarding fuel cycle back end.

These three groups operate either separately from each other or synergistically in order to create a global architecture for innovative NESs:

- the general strategy of NG1 countries is to recycle SNF — the group plans to build, operate and manage SNF recycling facilities and permanent geological disposal facilities for highly radioactive waste;
- the general strategy of NG2 countries is to either directly dispose of SNF or reprocess SNF abroad — the group plans to build, operate and manage permanent geological disposal facilities for highly radioactive waste (in the form of SNF and/or reprocessed waste) and/or it plans to work synergistically with another group to have its fuel recycled;
- the general strategy of NG3 countries is to use fresh fuel and send SNF abroad for either recycling or disposal, or the back end strategy is undecided — the group has no plans to build, operate and manage SNF recycling facilities or permanent geological disposal facilities for highly radioactive waste. NG3 countries may import fabricated fuel and may arrange for export of their SNF.

This principle for group division was developed in the GAINS collaborative project [XXI-7]. For more comprehensive analysis, two variants of the groups' ratio were considered: 40-40-20 and 60-20-20, see Fig. XXI-11 and Fig. XXI-12. This allows assessing a situation when one or several countries switch from an open fuel cycle strategy to the closed one.

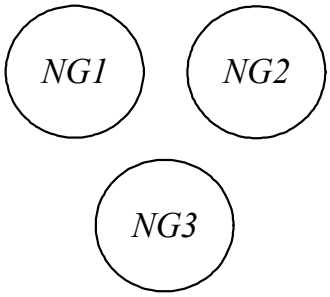


FIG. XXI-11. Heterogeneous non-synergistic model.

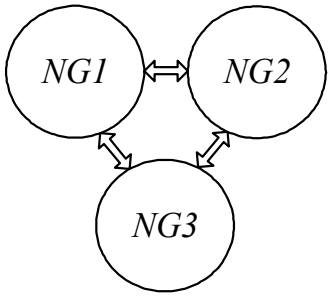


FIG. XXI-12. Heterogeneous synergistic model.

The selected ratio between groups is fixed till 2100.This condition obviously applies certain restrictions; however, it allows to analyze different possibilities with a given group ratio. Power capacities of NPPs for different ratio cases are presented in Tables XXI-4 and XXI-5.

TABLE XXI-4. NOMINAL SCENARIO OF NUCLEAR ENERGY GENERATION FOR HIGH AND MODERATE DEMAND CASES (NG1-NG2-NG3: 40-40-20 %)

Group	GW(e)·year						
		Moderate case			High case		
	2008	2030	2050	2100	2030	2050	2100
NG1	149	285	455	1000	333	682	2000
NG2	149	285	455	1000	333	682	2000
NG3	0	30	90	500	34	136	1000
World total	298	600	1000	2500	700	1500	5000

TABLE XXI-5. NOMINAL SCENARIO OF NUCLEAR ENERGY GENERATION FOR HIGH AND MODERATE DEMAND CASES (NG1-NG2-NG3: 60-20-20 %)

Group	GW(e)·year						
		Moderate case			High case		
	2008	2030	2050	2100	2030	2050	2100
NG1	149	313	545	1500	364	814	3000
NG2	149	260	367	500	302	550	1000
NG3	0	30	90	500	34	136	1000
World total	298	600	1000	2500	700	1500	5000

The calculated results were compared for homogenous and heterogeneous synergistic and non-synergistic cases, to assess their sensitivity to group ratio.

XXI-3.2. VVER-S

Global consideration allows to get optimistic assessment of fast reactors' share in nuclear energy structure, including reduction of annual natural uranium consumption, capacities of separation plants, volume of SNF, etc.

At the same time, group consideration without collaboration between them gives bottom estimate of all of the parameters mentioned, and the difference is world losses due to renouncement of collaboration in nuclear energy. The cases of different level of collaboration between groups are studied.

Each case is described in the following way:

- Reactor type – LWR, ALWR, HWR, FR, VVER-S;
- Every period is modelled by linear law in reaching the defined power capacity level, see Table XXI-6;

TABLE XXI-6. POWER CAPACITIES CHANGE

Moderate case	High case
2009 – 2030: 600 GW(e)·year 2031 – 2050: 1000 GW(e)·year 2051 – 2100: 2500 GW(e)·year	2009 – 2030: 700 GW(e)·year 2031 – 2050: 1500 GW(e)·year 2051 – 2100: 5000 GW(e)·year
to 2030 – 10 GW(e)·year; to 2050 – 200 GW(e)·year; to 2100 – maximum power capacity that plutonium reserves allow to have.	- to 2030 – 10 GW(e)·year; - to 2050 – 400 GW(e)·year; - to 2100 – maximum power capacity that plutonium reserves allow to have.

– Reactors distribution by groups:

- 1st group: LWR, ALWR, VVER-S, FR;
- 2rd group: LWR, ALWR, VVER-S, HWR;
- 3rd group: ALWR, VVER-S;

– ALWRs are assumed to be deployed in 2013;
– VVER-Ss are assumed to be deployed in 2025;
– FRs are assumed to be deployed in 2020;
– Length of external fuel cycle (storage + reprocessing) for thermal reactors – 6 years, for FRs – 3 years.

Calculations were performed for homogeneous and heterogeneous (non-synergistic and synergistic) cases.

XXI-3.3. Moderate scenario

Figures-XXI-13 and XXI-14show power production distribution by group depending on selected group ratio.

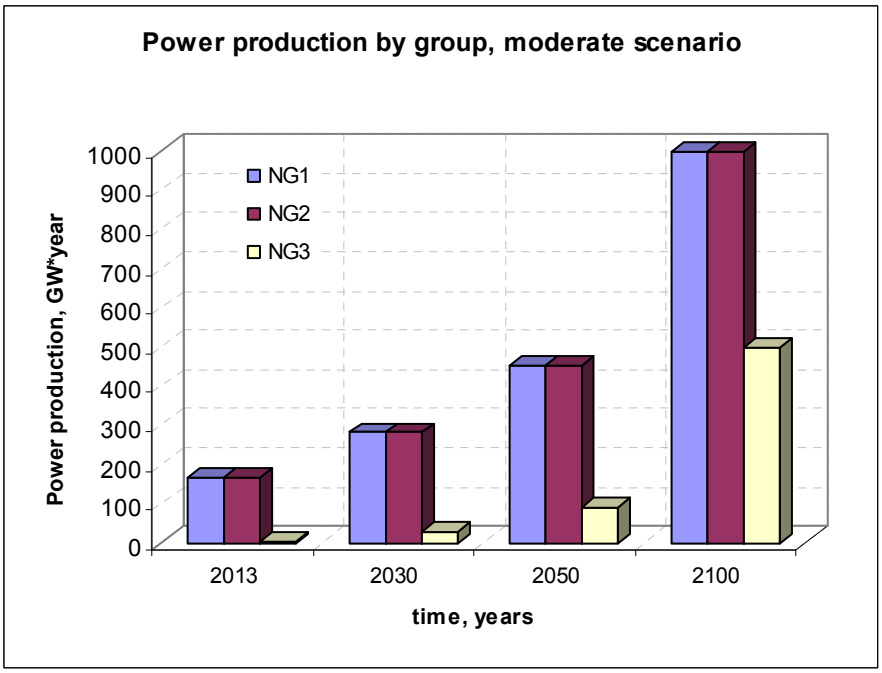


FIG. XXI-13. Power production, heterogeneous non-synergistic moderate case, showing production by group (40-40-20).

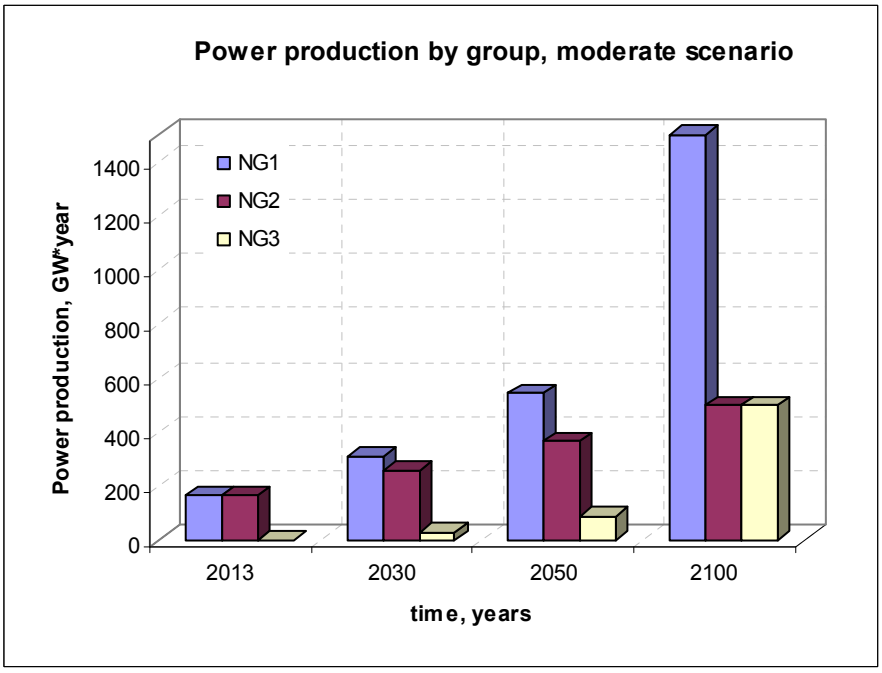


FIG. XXI-14. Power production, heterogeneous non-synergistic moderate case, showing production by group (60-20-20).

There is collaboration between NG1 and NG3, so a half of SNF from NG3 thermal reactors is reprocessed in NG1 with extraction of plutonium for further use in NG1 fast reactors. This approach allows increasing FRs' share due to larger amount of available plutonium, see Fig. XXI-15.

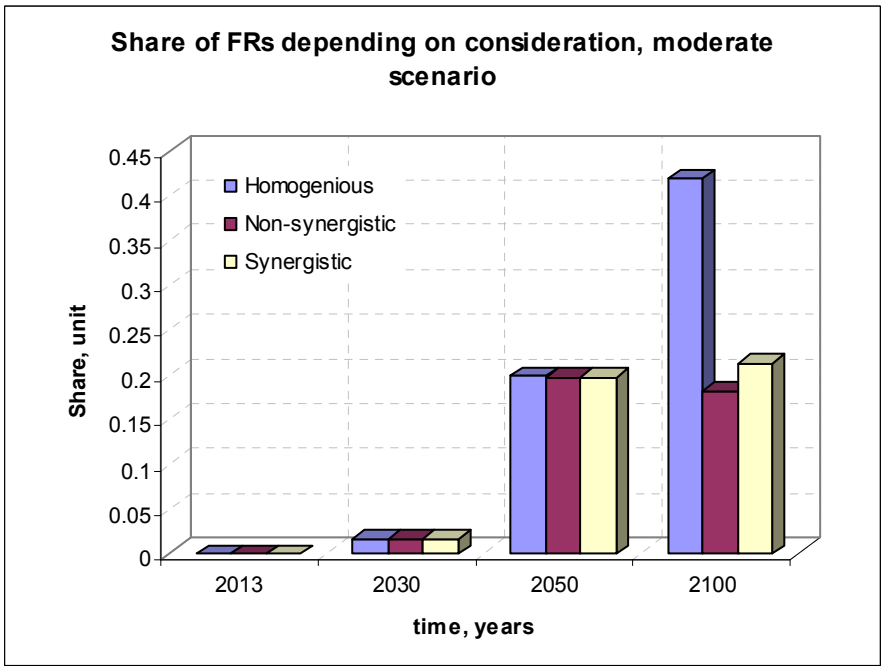


FIG. XXI-15. Share of FRs depending on case, moderate scenario (group division is 40-40-20).

Share of FRs in nuclear energy structure is almost 42% for homogenous scenario. This value is the maximum FR share for considered conditions. For heterogeneous non-synergistic case, the FRs share is approximately 18% which is predictable, as only 20% of the thermal

reactors' SNF (from NG1) is reprocessed. Collaboration between groups allows to slightly reduce the difference with global consideration, by 3%.

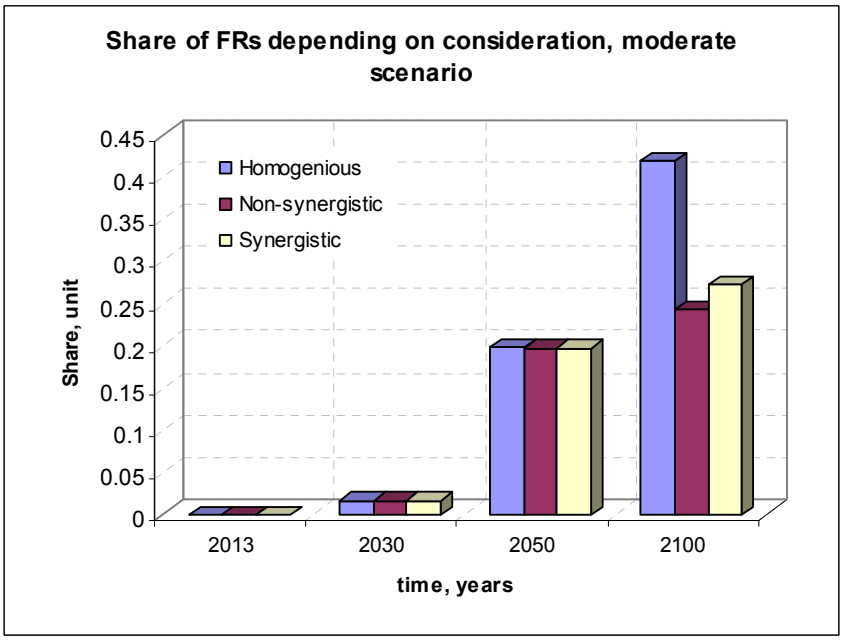


FIG. XXI-16. Share of FRs depending on case, moderate scenario (group division is 60-20-20).

The higher share of FRs (24 %) is possible in case of other ratio between groups due to larger volume of SNF from thermal reactors available for reprocessing, see Fig. XXI-16. In addition, collaboration between countries helps converging the results for homogeneous and heterogeneous cases. However, the difference between non-synergistic and synergistic scenarios is not significant in given conditions; hence, VVER-S effect is negligible without FRs upgrade.

Reduction of natural uranium consumption and SNF accumulation are some of the objectives of fuel cycle closing.

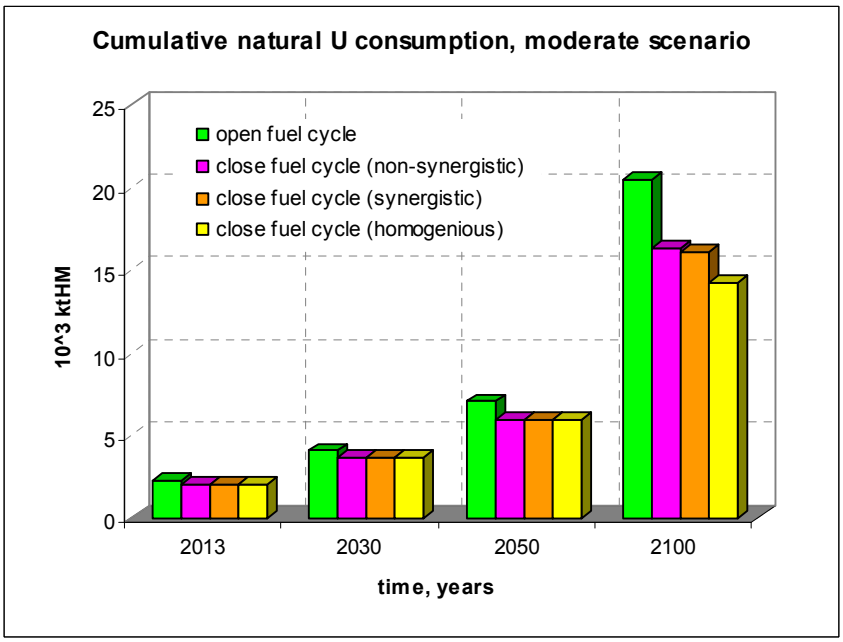


FIG. XXI- 17. Cumulative natural U consumption – moderate scenario.

Figure XXI-17 presents cumulative natural uranium demand. Closed fuel cycle allows a reduction in natural reserves use down to 17%, independently of the chosen approaches. So, the nuclear energy system described (for moderate case) is sustainable till the end of century in terms of resources.

In addition, an increase in the number of countries operation in a closed fuel cycle admits reduced natural uranium consumption. However, the value of this saving is insignificant (about 2.5%), so redistribution of power capacities between groups practically does not have an effect on the size of natural recourses shortage.

Main savings of uranium arise from NG1, where closed fuel cycle is implemented, see Fig. XXI-18.

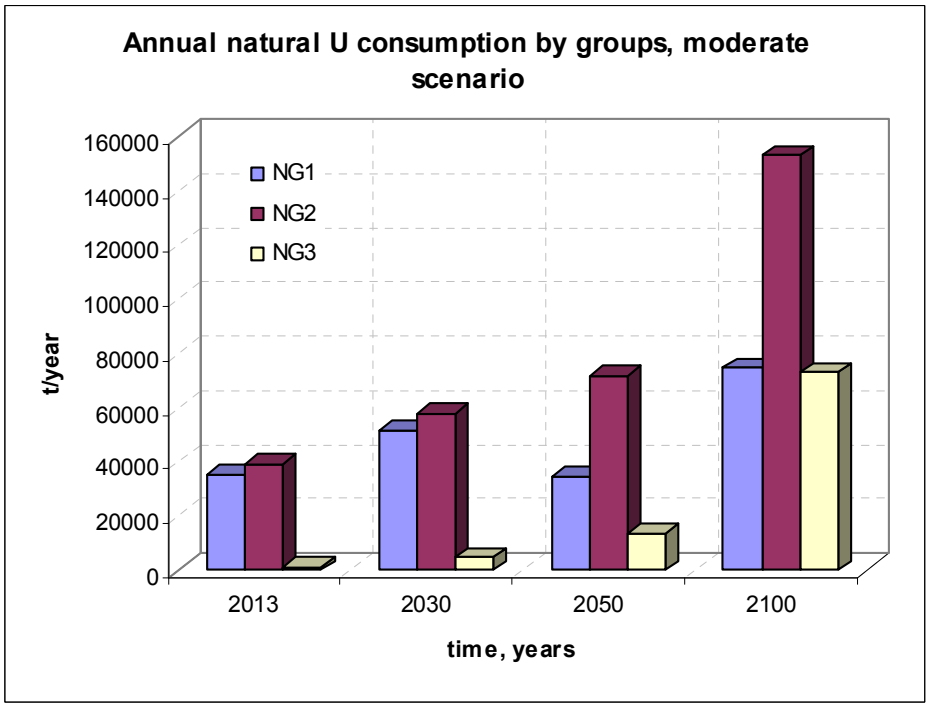


FIG. XXI-18. Annual natural U consumption by groups, heterogeneous non-synergistic case, moderate scenario (40-40-20).

Figure XXI-18 shows that, with equal power production in NG1 and NG2, annual natural uranium consumption by NG1 is twice lower in comparison with NG2. This fact is obviously related to FRs in NG1 having a share of almost half of power production.

There are other results for the 60-20-20 ratio, see Fig. XXI-19. The material balances for NG3 did not change because power production for this group remained at 20%. The reactors' share in NG2 decreased twice, which obviously reduced annual natural uranium consumption, separative work, etc. It should be noted that HWRs have been and remain deployed in the NG2, which results in higher consumption of natural resources than in NG3. At the same time, HWRs require less separative work. Use of VVER-Ss in NG1 allows increasing the FBRs share to 6% due to extraction of additional plutonium from SNF of thermal reactors.

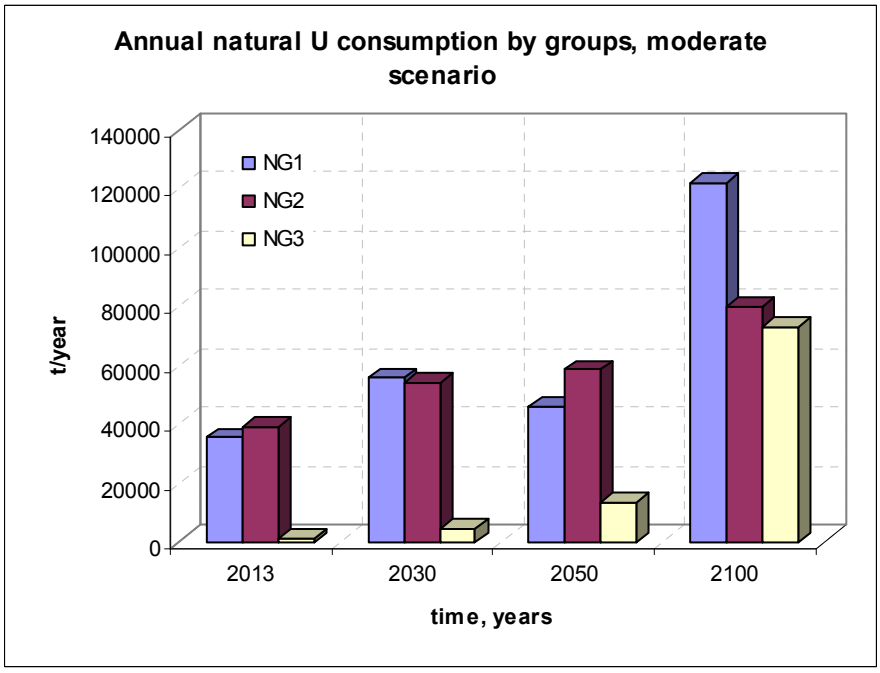


FIG. XXI- 19. Annual natural U consumption by groups, heterogeneous non-synergistic (60-20-20) moderate scenario.

In spite of the fact that power production in NG2 and NG3 is equal, annual uranium consumption in NG2 is higher because of HWR. As a whole, these redistributions between groups almost do not impact cumulative consumptions and they remain invariable independent of the chosen approach.

As noted above, closing of a fuel cycle is necessary for SNF volume reduction. Figures XXI-20 and XXI-21 show the results of SNF volume calculations for different approaches.

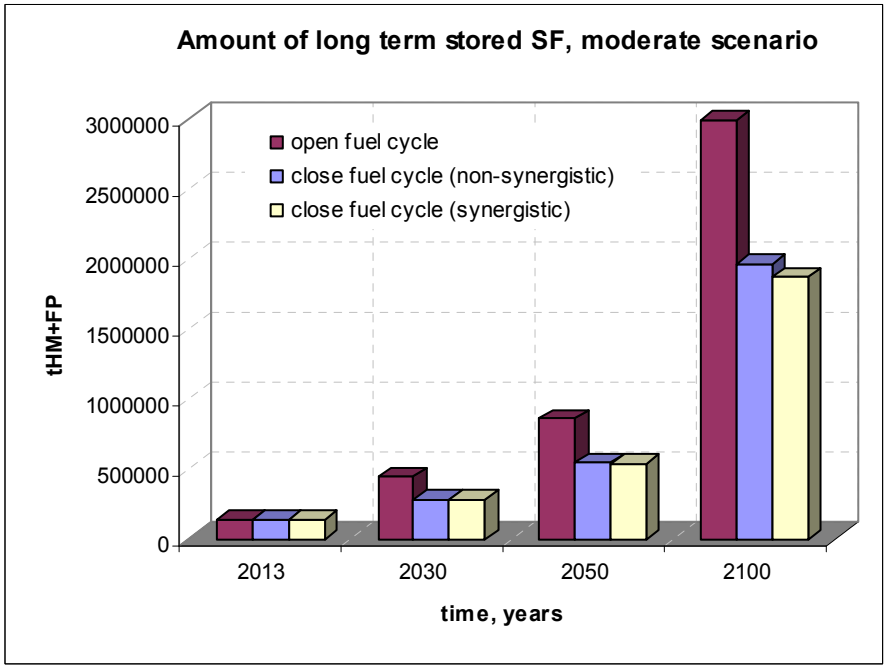


FIG. XXI-20. Amount of long term stored SNF depending on case, moderate scenario (group division is 40-40-20).

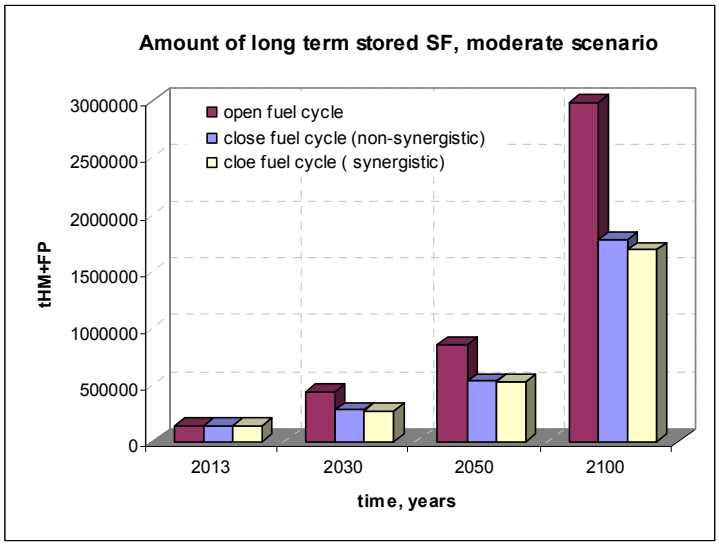


FIG. XXI-21. Amount of long term stored SNF depending on case, moderate scenario (group division is 60-20-20).

For moderate scenario the volume of cumulative SNF achieves 3 million tons by 2100 for open fuel cycle. Closing of fuel cycle allows to significantly reduce this value (35-40%) depending on NG1 share and the level of collaboration with NG3. Figures XXI-20 and XXI-21 demonstrate that principal SNF volume reduction is the result of fuel cycle closing; collaboration between countries has only slight influence. It should be noted that one third of all SNF originates from HWRs and will not be reprocessed. But, at the same time, this SNF has low level of radioactivity due to low level of burn-up.

Obviously, fuel cycle closure allows reducing not only natural uranium consumption, but also separative work.

XXI-3.4. High scenario

Distribution of power production between groups according to chosen ratios is shown in Figures XXI-22 and XXI-23. The total annual power production reaches 5000 GWyear by 2100.

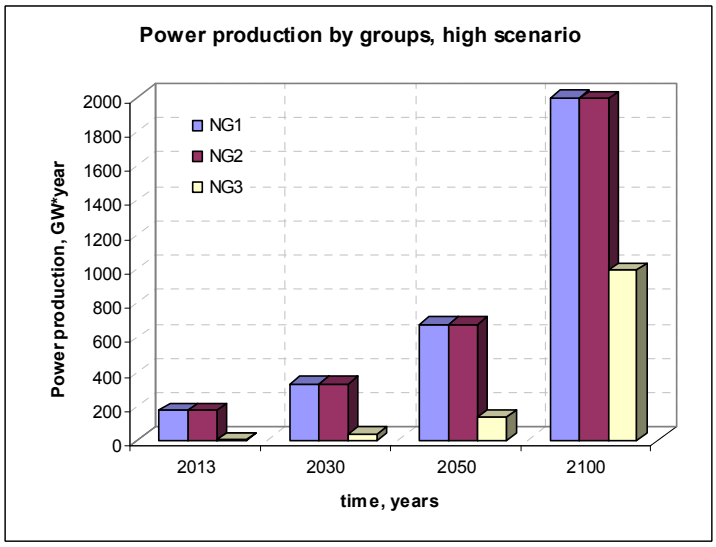


FIG. XXI-22. *Power production by group, heterogeneous non-synergistic high case (40-40-20).*

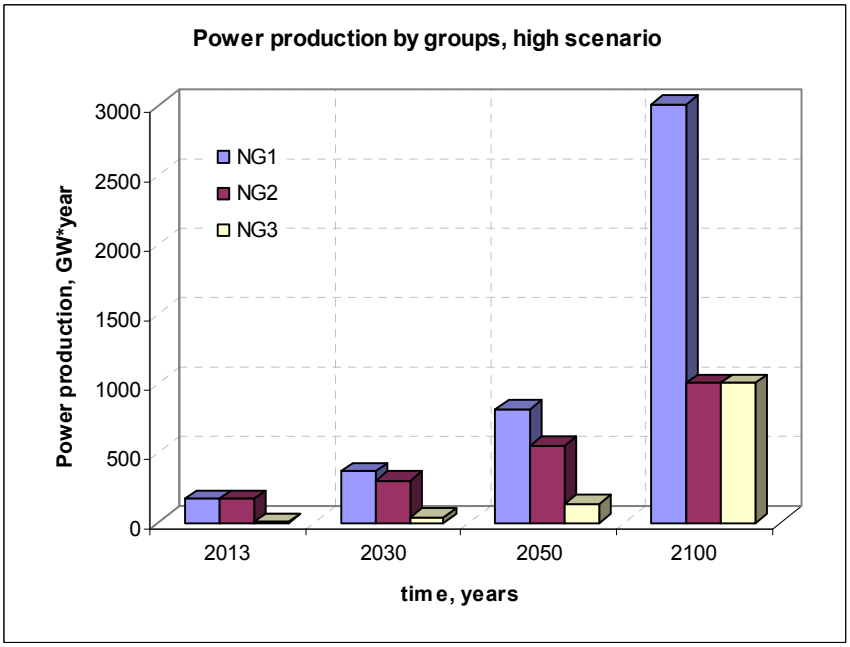


FIG. XXI-23. Power production by group, heterogeneous non-synergistic high case (60-20-20).

Similarly to moderate scenario, part of SNF from NG3 is reprocessed in NG1 together with extraction of plutonium. It should be noted that the share of FRs is less by 10 % for high case in comparison with the moderate case. Apparently, it is caused by higher power production growth with the equal amount of extracted plutonium (Figures XXI-24 and XXI-25).

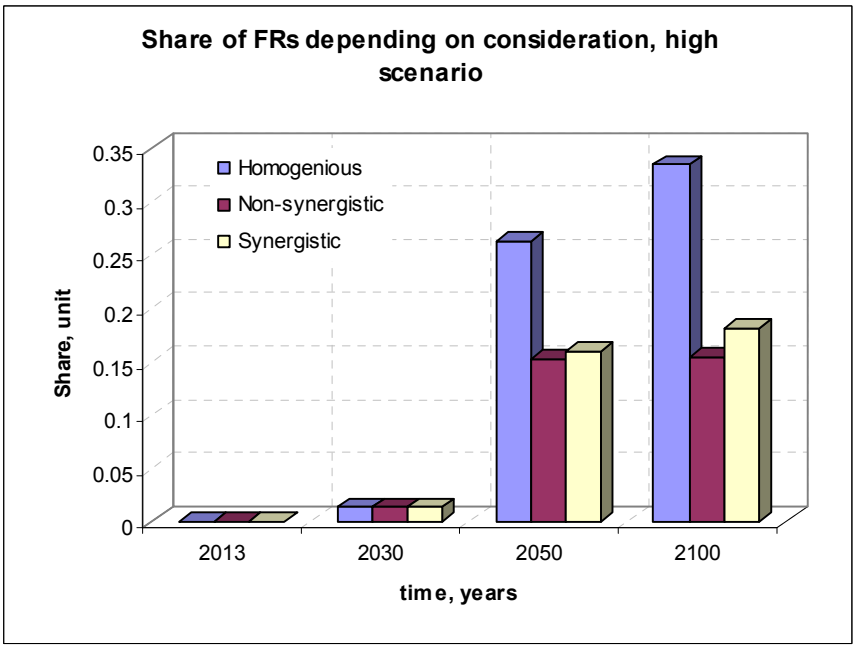


FIG. XXI-24. Share of FRs depending on case, high scenario (group division is 40-40-20).

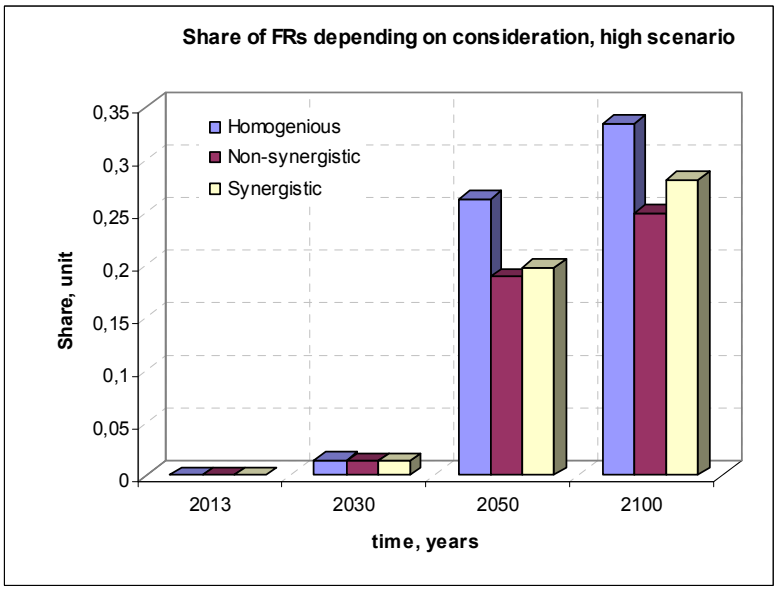


FIG. XXI-25. Share of FRs depending on case, high scenario (group division is 60-20-20).

The share of FRs in nuclear energy structure is 33% for homogeneous case. This value is the maximum estimation of FRs' share for defined conditions. For heterogeneous case, FRs' share reaches almost 14%. Collaboration between groups slightly impacts nuclear energy structure. Under the high scenario, redistribution of power capacities between groups influences nuclear energy structure more significantly. Increase of reactors' share in NG1 allows to enlarge FRs' share almost up to the maximum value in a synergistic case.

Figure XXI-26 demonstrates the influence of fuel cycle closing and collaboration between countries on saving of natural resources.

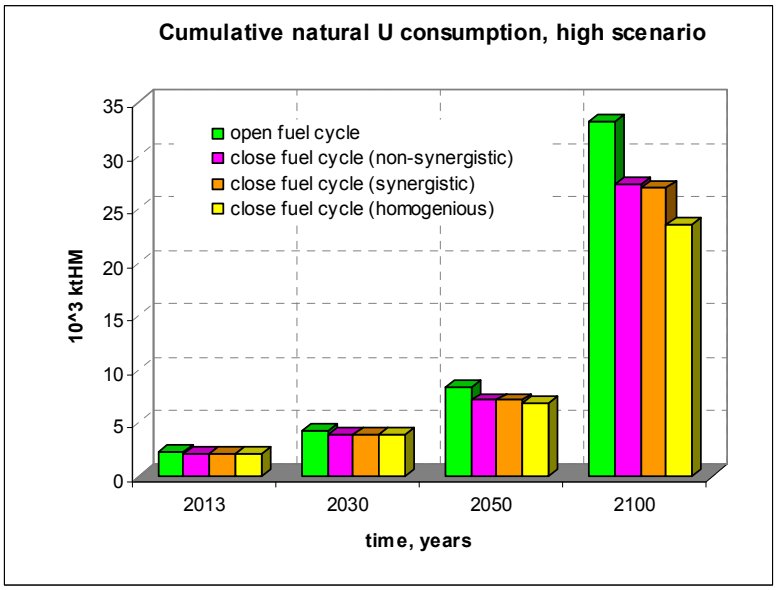


FIG. XXI-26. Cumulative natural U consumption – high scenario.

Closing of fuel cycle leads to a reduction of natural uranium resources' use by 20 %, depending on chosen approach. However, it should be noted that even the use of VVER-Ss does not provide enough economy of natural uranium, and the uranium demand exceeds its reserves under high scenario.

Increase in the of countries number working in a closed fuel cycle allows to additionally reduce uranium consumption. For high scenario the value of saving is only 2.5%, so redistribution of power capacities between groups does not influence the resources' shortage. Figure XXI-26 shows that the accepted limit of 20 million tons is not achieved for chosen structure even with maximum collaboration between countries. In this case the problem of resources' exhaustion may be solved by use of FRs with higher breeding ratio. This approach, however, is beyond the scope of this study.

Power production growth is accompanied by accumulation of SNF. Double power growth leads to SNF volume increase by 50 % by the end of the century. Closing of fuel cycle compensates it to a certain extent. Figures XXI-27 and XXI-28 show changes of SNF volume in time for different approaches.

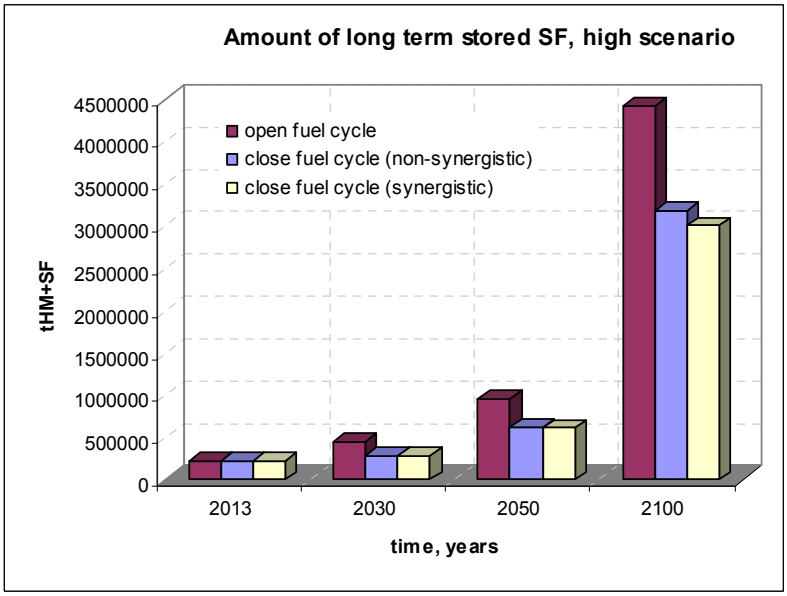


FIG. XXI-27. Amount of long term stored SNF depending on case, high scenario (group division is 40-40-20).

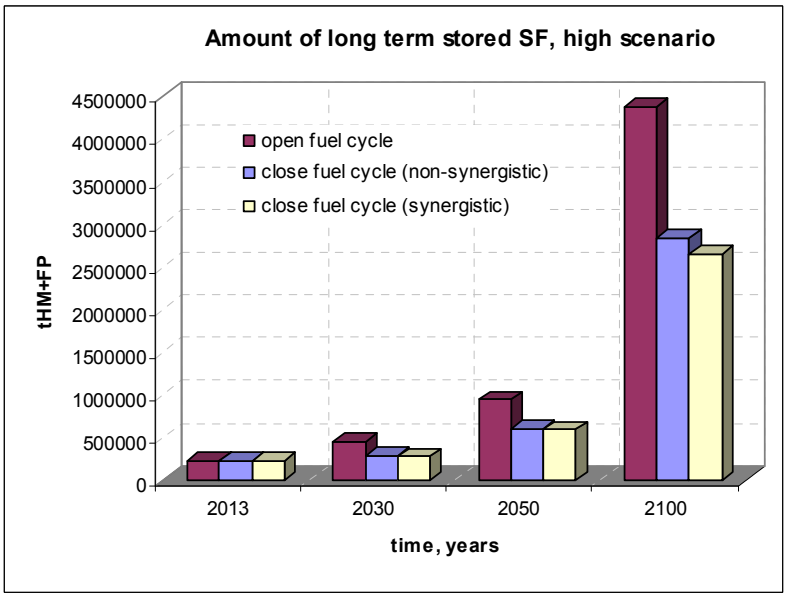


FIG. XXI-28. Amount of long term stored SNF depending on case, high scenario (group division is 60-20-20).

It is obvious that increase of power capacities in NG1 and, therefore, increase of reprocessed SNF volume, result in a reduction of SNF volume for the entire system. SNF share in NG3 is relatively small, so collaboration with this group has almost no influence on material balance of the nuclear energy system.

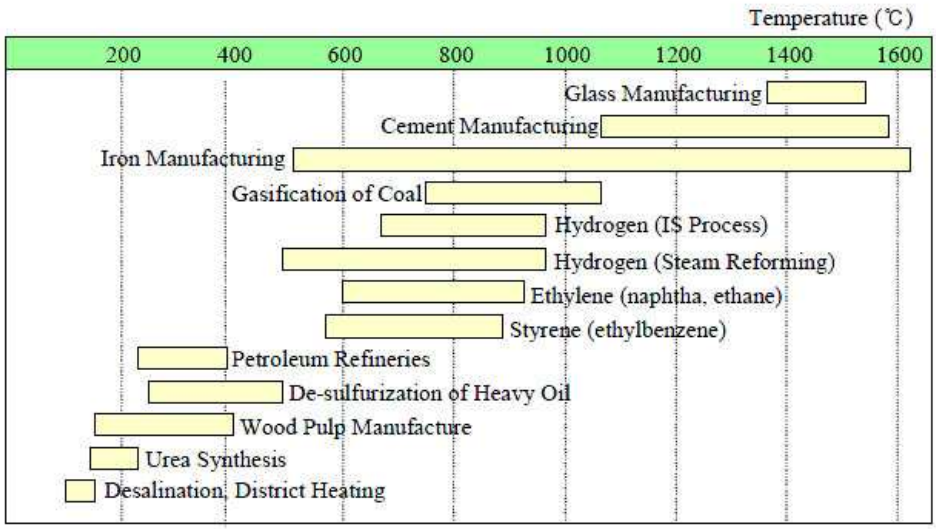
XXI-3.5. Conclusions to section XXI-3

For the moderate case, the analysis shows that nuclear energy system with the VVER-Ss, which have high thermal efficiency and breeding ratio, and the FRs with BR~1 is sustainable within the frames of the accepted limitations, and this structure is capable to significantly reduce the SNF volume. But for the high case, the use of VVER-Ss is not sufficient and, along with thermal reactors upgrade, it is necessary to deploy FRs with higher breeding ratio.

It was demonstrated that involvement of countries in a closed fuel cycle and reprocessing of SNF from countries with open fuel cycle allows using natural resources more efficiently, reduce separation plants capacities and the volume of SNF, and better use the extracted plutonium.

XXI-4. NON-ELECTRICAL APPLICATIONS

Nuclear power plants have different variants of heat application depending on the steam temperature they produce. Figure XXI-29 shows the areas of possible steam application.



SOURCE: NON-ELECTRICITY PRODUCTS OF NUCLEAR ENERGY, OECD/NEA, 2004

FIG. XXI-29. Areas of heat application depending on temperature.

In general, reactors produce steam with temperature less than 400 ºC, so application in terms of co-generation of NPPs is usually considered from desalination and heat supply points of view. At the same time, there are reactors with steam temperature of approximately 800 ºC; in such a case application area of these reactors in industry is significantly enlarged.

XXI-4.1. Small and medium sized reactors

In this study, application of small reactors for seawater desalination was considered. This issue is critical due to worldwide shortage of fresh water. In some European countries with high level of agriculture water became unsuitable for traditional use because of

fertilizers, which also results in fresh water shortage [XXI-8]. Moreover, population growth and rise of living standards cause growth of fresh water consumption.

In the UNESCO report 'Water in a changing world' [XXI-9] it is written that some countries achieved extreme level of water use, and the current climate change just exacerbates the situation. This may result in a fight between countries and cities for water resources. In the end, this problem may escalate from water resources area to a political level. According to the UN assessment, 5 billion people will not have water with satisfactory quality in 2030, if current situation continues. It is about 67 % of the world population.

Figure XXI-30 shows availability of fresh water in the regions. As shown, the maximum shortage of fresh water is in Africa, in the Middle East countries and in China.

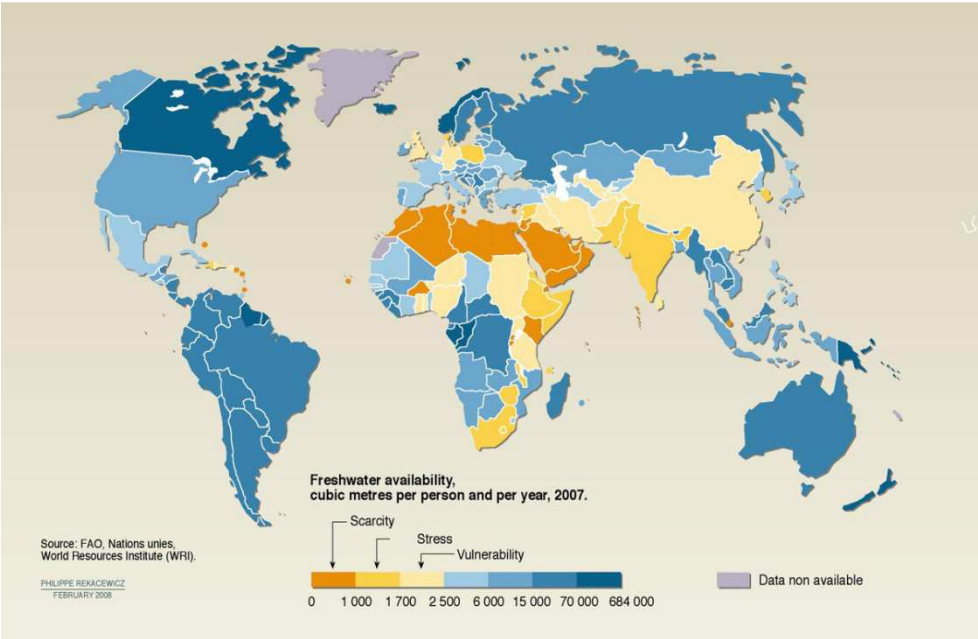


FIG. XXI-30. Fresh water availability, m^3/man/year.

However, many countries have learnt to deal with fresh water shortage via seawater desalination. The list of ten largest desalination plants is presented in Table XXI-7.

TABLE XXI-7. THE LARGEST DESALINATION PLANTS [XXI-10]

Country	Capacity, m^3/day
Saudi Arabia	880 000
Saudi Arabia	800 000
Saudi Arabia	730 000
UAE	600 000
Kuwait	567 000
UAE	450 000
UAE	454 600
USA	454 200
UAE	454 000
UAE	454 000

According to the DesalData [XXI-11], there are more than 15 000 desalination plants in total with installed capacity of 60 million m^3/day. Additional desalination capacities (almost 10 million m3/day) are under construction.

Location of the desalination plants in the world is presented in the map in Fig. XXI-31.

SOURCES: ENGINEERING NEWS-RECORD AQUA RESOURCES INTERNATIONAL CORP.; INTERNATIONAL DESALINATION ASSOCIATION

FIG. XXI-31. The map of desalination plant worldwide.

As seen, most desalination plants are located in South America and in Africa. According to heterogeneous consideration, these countries may be referred to as NG3, i.e., countries which had not defined further strategy of SNF management and, therefore, would pass their SNF to NG1 and NG2 groups of countries.

It was assumed that part of NPPs is aimed for water desalination. Small and medium sized reactors (SMRs) could be considered for this purpose. According to the IAEA definition, small reactor is a reactor with power capacity less than 300 MW(e). Main advantages of such reactors include:

- longer fuel residence time;
- short construction period;
- low specific power density and higher reliability;
- load following operation mode;
- compactness;
- reduced reliance on of water resources, etc. [XXI-12].

One of SMRs for water desalination is the Russian reactor KLT-40 currently in the final stage of construction. Specifications of KLT-40 are presented in Table XXI-8. The isotopic composition of KLT-40 reactor used for calculation is presented in Appendix I to this Annex.

Production of 1 kg of fresh water requires 300-400 kJ of heat, i.e., two reactor units may produce 8000-10 000 m^3/day. In this study, the SMRs' share in total desalination capacity is 1/5; their share in world nuclear electricity production is 15-20 %. It means that SMR power production is about 7 % of the power production from all thermal capacities under moderate scenario. For high case it is possible to increase fresh water production twice, so that SMRs' share will be 7 % in the nuclear energy structure.

As mentioned above, SMRs were considered to be implemented in NG3 and planned to be launched in 2020, replacing half of the thermal reactors in this group of countries. For model simplification it is assumed that VVER-Ss start operation from current year. In fact, their start was planned for 2025, but the share of ALWRs that may operate from 2013 to 2025 was insignificant and produced only a slight impact on material balances of the nuclear energy system. Figures XXI-33 and XXI-34 present thermal power production of NPPs for moderate case variants with and without co-generation. The results are presented for heterogeneous non-synergistic case.

TABLE XXI-8. MAIN SPECIFICATIONS OF KLT-40

Reactor specifications	Value
Reactor net electric output, MW	38.5
Reactor thermal output, MW	150
Thermal efficiency, %	25.7
Average load factor, %	70
Operation cycle length, effective full power days (EFPD)	583
Enrichment, %	14.1
Specific power density, MW/t	115
Initial core inventory, tHM	1.2728
Share of heat (option):	
- electricity, %	56
- desalination, %	44

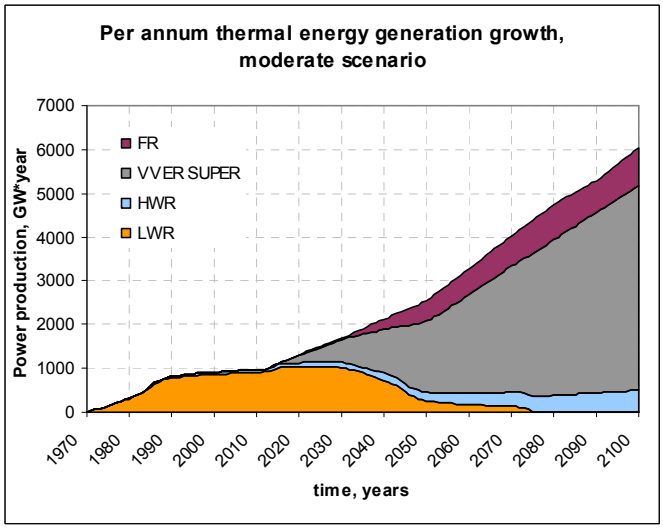


FIG. XXI-32. Thermal power production (moderate scenario).

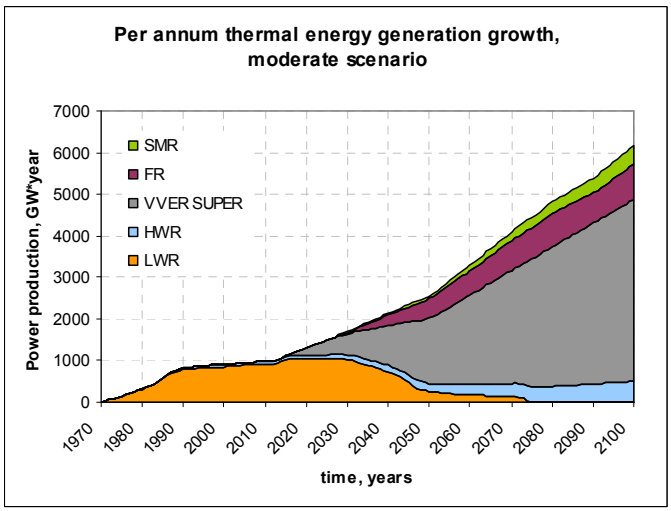


FIG. XXI-33. Thermal power production with co-generation (moderate scenario).

Figures XXI-32 and XXI-33 show that thermal power production is higher for co-generation scenario of nuclear energy. Therefore, to save electricity production it is necessary to increase thermal production in co-generation applications.

Interaction with NG3 assumes partial reprocessing of its SNF in NG1 and final disposal of the rest in NG2. In the framework of this study, the SNF of SMRs was assumed to be not reprocessed because of its small volume.

It is obvious that power capacity growth results in natural uranium consumption increase. Figure XXI-34 demonstrates cumulative uranium consumption till the end of century for basic and co-generation scenarios.

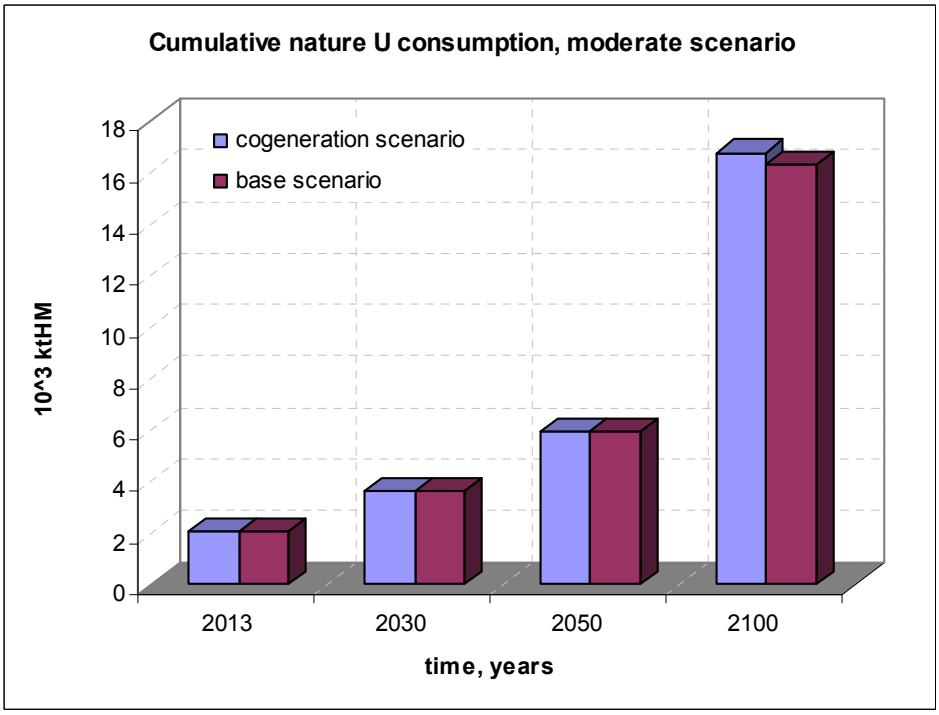


FIG. XXI-34. Cumulative natural U consumption – moderate scenario.

SMRs have lower values of fuel utilization characteristics because of their features, but their application is necessary for expansion of nuclear energy applications, especially in developing countries. Without SMRs, sustainable development and widening of resource base is almost impossible. As shown, non-electrical applications of nuclear energy in the chosen scale does not influence significantly the consumption of resources. Besides, this difference may become smaller in case of reprocessing of SMR SNF.

There is no difference between non-co-generation and co-generation scenarios for the chosen approaches: the share of power production is 20 % for NG3 and SMR SNF is not reprocessed.

Obviously, larger volume of SNF is accumulated in this system, and natural uranium consumption increases, see Fig. XXI-35.

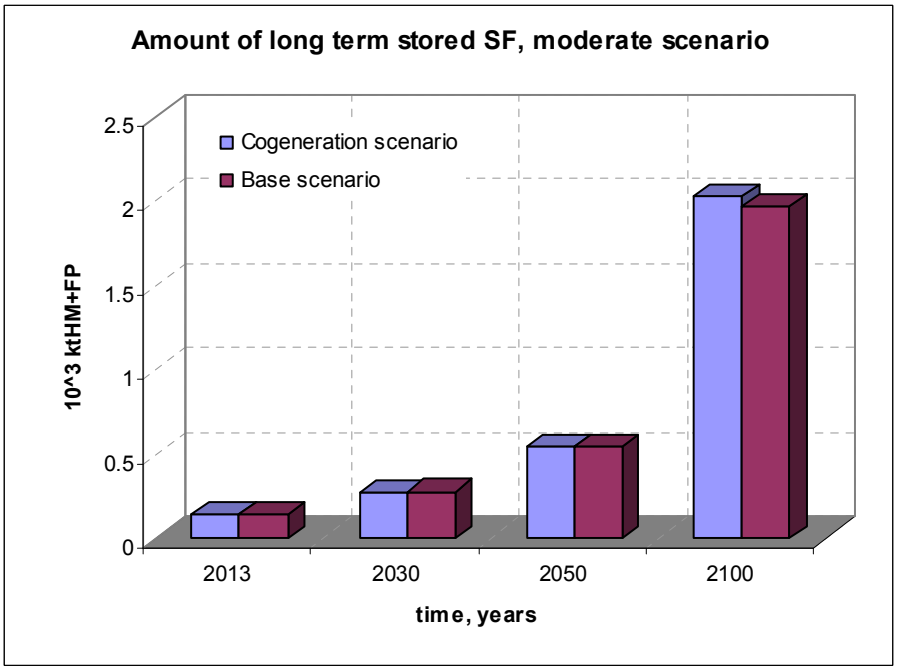


FIG. XXI-35. Amount of long term stored SNF – moderate scenario.

It should be noted that the difference between the volumes of SNF is insignificant for non-electrical and electrical applications of nuclear energy, and this difference may be less in the case of SMR SNF reprocessing.

Figure XXI-36 shows the structure of SNF volume for different reactor types.

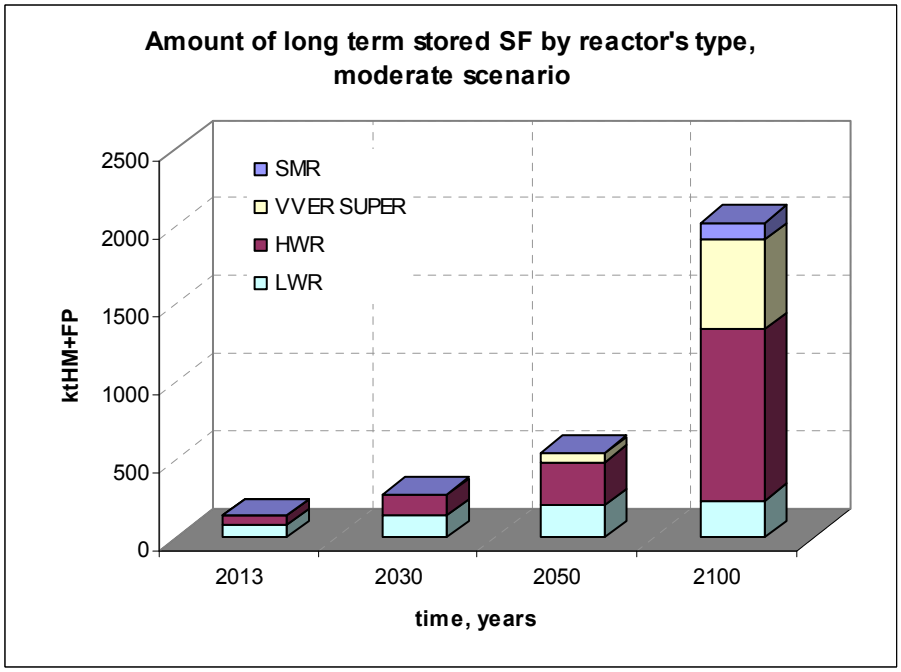


FIG. XXI-36. Amount of long term stored SNF by reactor type – moderate scenario.

For heterogeneous non-synergistic case, the total volume of SNF is distributed between NG2 and NG3. Despite HWRs' share being 6 % in the nuclear energy system, their part of SNF is approximately 50 % of the total. Nevertheless, due to its low level of radioactivity this SNF has low decay heat, see Fig. XXI-37.

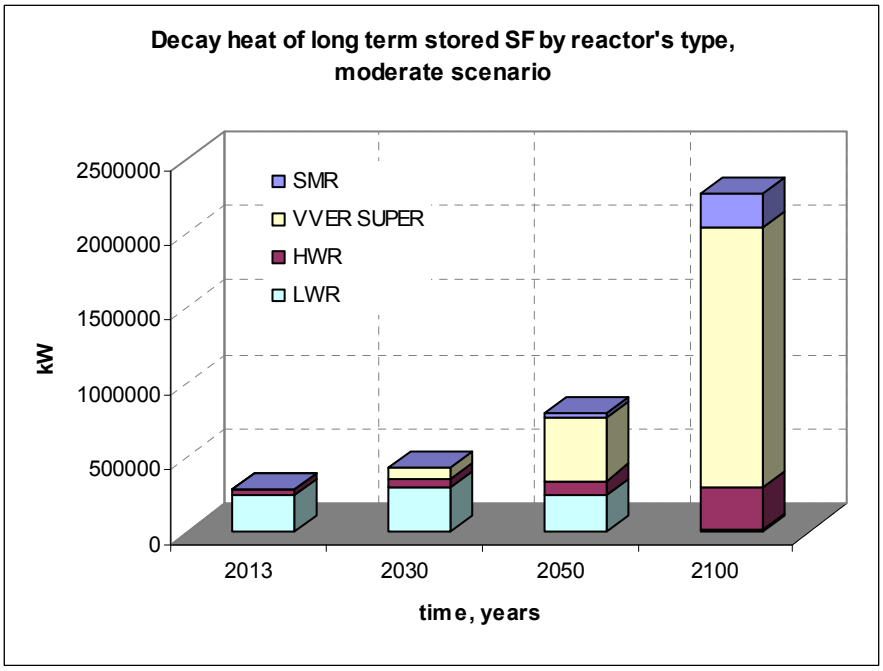


FIG. XXI-37. Decay heat of long term stored SNF by reactor type – moderate scenario.

The general picture is the same for high case scenario. Obviously, natural uranium demand increases and system cannot satisfy it because of resource limitations. Growth of thermal reactor power capacities and the part of SNF from reactors that is not reprocessed result in an increase of SNF volume and decay heat.

XXI-4.2. High temperature reactors

Other possible variant of non-electrical applications of nuclear energy is heavy oil production.

Over the past ten years the quality of new oilfields has decreased, and now they mainly consist of heavy oil reserves. At the same time, these reserves significantly exceed oil reserves with small and middle viscosity. Figure XXI-38 shows the distribution of heavy oil reserves by regions [XXI-13].

According to the U.S. Geological Survey data, the world heavy oil resources amount to 3400 billion barrels. As shown in Fig. XXI-39, main oil reserves are located in South America and in the Middle East.

Steam pumping technologies are applied for heavy oil production [XXI-14]. Apart from oil extraction, it is required to improve its quality to light oil. For this purpose it is necessary to add hydrogen. In average, 1 ton of heavy oil is needed for 70-90 kg of hydrogen in this process.

It should be noted that the oil, produced in this way, cannot be transported through pipeline, so its primary processing is necessary. Taking into account that for oil processing steam with temperatures 700 - 850°C is required, only high temperature reactors (HTR) could provide the conditions needed.

According to expert estimations, NPPs with HTR units with total thermal capacity of 3000 MW may produce the following products in case of co-generation application, see Table XXI-9.

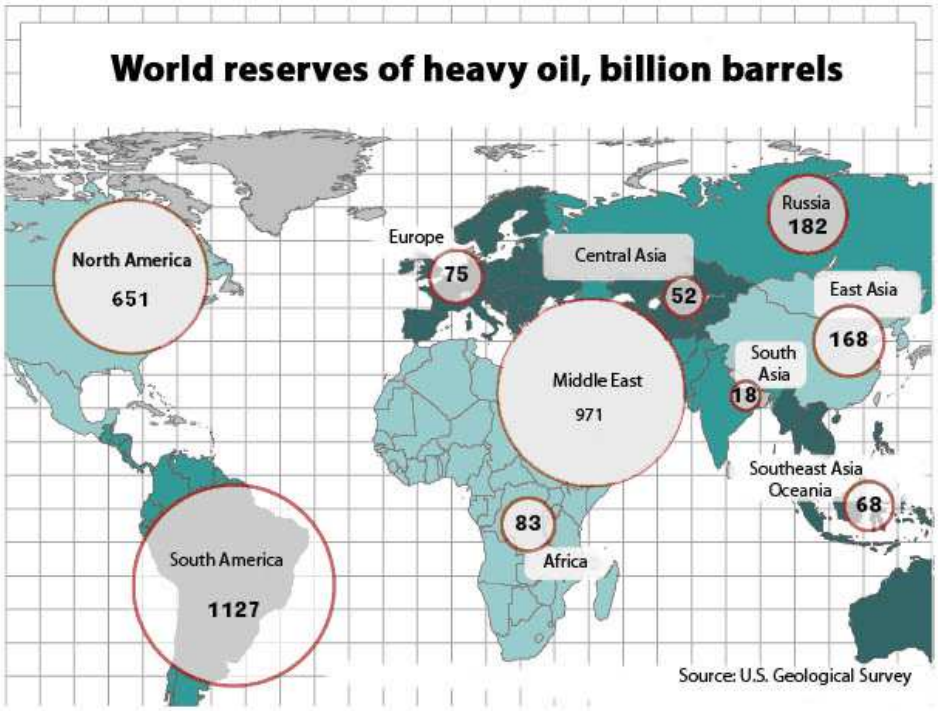


FIG. XXI-38. World reserves of heavy oil.

TABLE XXI-9. APPLICATION STRUCTURE OF HTR STEAM

Area	Value	Unit	%
Steam	1740	t/hour	29
Heavy oil production	348	t/hour	
Hydrogen production	24.3	t/hour	54
Electricity production	230	MW	17

Table XXI-9 shows that half of energy is spent on hydrogen production necessary for transfer of heavy oil to light oil. Application of nuclear energy in this area allows saving hydrocarbons and reduction of gas emissions to environment from organic fuel application for heavy oil production.

According to the expert assessment, annual heavy oil production equals 1 billion tons and it requires 1000 GW of HTRs' thermal capacity. Considering that the share of electricity production for these plants will be lower, thermal power capacities should be slightly higher in comparison with non-co-generation scenario.

HTR is one of the most perspective directions of reactors development, capable to satisfy safety and non-proliferation requirements. These plants belong to Generation IV reactors and could start operation before 2020. HTRs are characterized by high thermal efficiency ~ 45 % and fuel high burn-up, supporting effective fuel utilization. In this study HTRs were assumed to operate with uranium fuel, but such reactors can operate with plutonium which might be useful in case of uranium shortage.

From SNF management point of view, HTRs are attractive as coated fuel particles are on themselves well prepared to long-term storage and disposal, possibly without additional reprocessing. Considering heavy oil distribution by regions and the absence of a need to reprocess HTR SNF, HTRs were assumed to be deployed in NG3 countries.

The characteristics of HTRs are presented in Table XXI-10 [XXI-15 and XXI-16].

TABLE XXI-10. MAIN SPECIFICATIONS OF HTR

Reactor specifications	Value
Reactor net electric output, MW	270
Reactor thermal output, MW	600
Thermal efficiency, %	0.45
Average load factor, %	85
Number of refuelling batches	Continued
Fuel residence time, EFPD	833
Enrichment, %	8
Specific power density, MW/t	100
Average discharge burn-up, MWday/t	83000
Initial core inventory, tHM	6
Equilibrium loading , tHM/year	6
Share of heat (option):	
Electricity, %	17
High temperature heat, %	83

The isotopic composition of HTR reactor used for calculation can be found in Appendix I to this Annex.

With the same assumptions as for the scenario with SMRs, in this case VVER-Ss are also introduced from the current year. Figures XXI-40 and XXI-41 present NPPs' thermal capacity for non-co-generation and co-generation moderate cases. Data is presented for heterogeneous non-synergistic case.

Figures XXI-39 and XXI-40 show that thermal capacities for co-generation and non-co-generation scenarios differ by 17 %. It is caused by the fact that most part of heat is used for co-generation in non-electrical applications of NPPs, but not for electricity production. In order to save 2500 GW of total electricity production by 2100, it is necessary to compensate the lack of electricity capacities by introduction of additional VVER-Ss. At the same time, the share of HTR thermal capacities will equal 14 % in nuclear energy structure and the share of HTR electric capacity will amount only to 3 %.

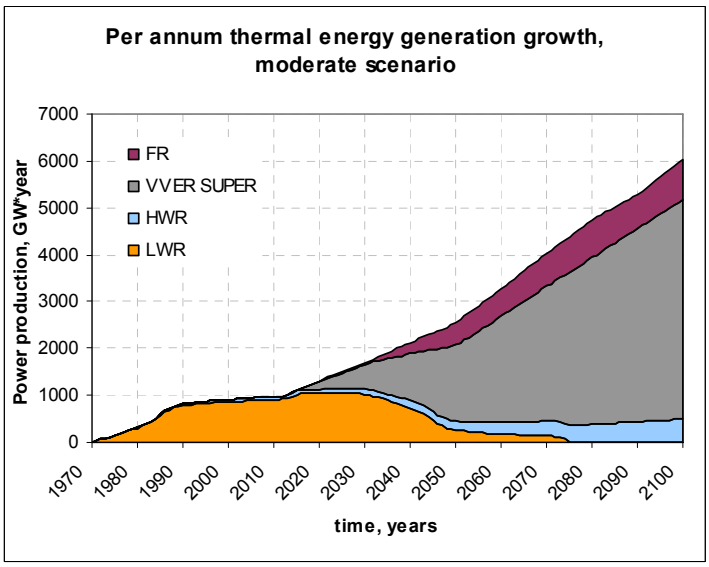


FIG. XXI-39. Thermal power production (moderate scenario).

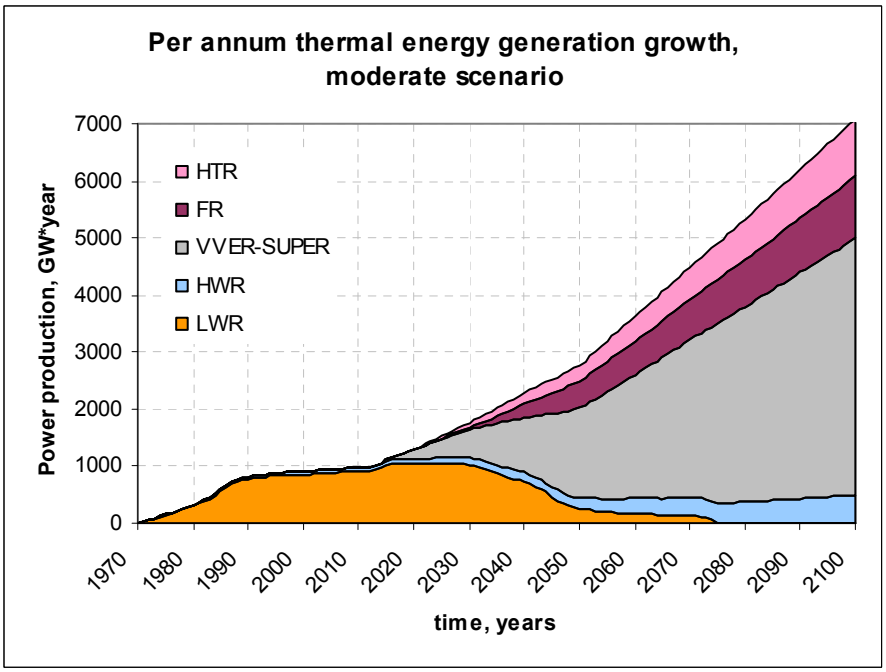


FIG. XXI-40. Thermal power production with co-generation (moderate scenario).

It is obvious that quite significant thermal capacity growth causes an increase of natural uranium consumption. Figure XXI-41 shows changes in cumulative uranium consumption.

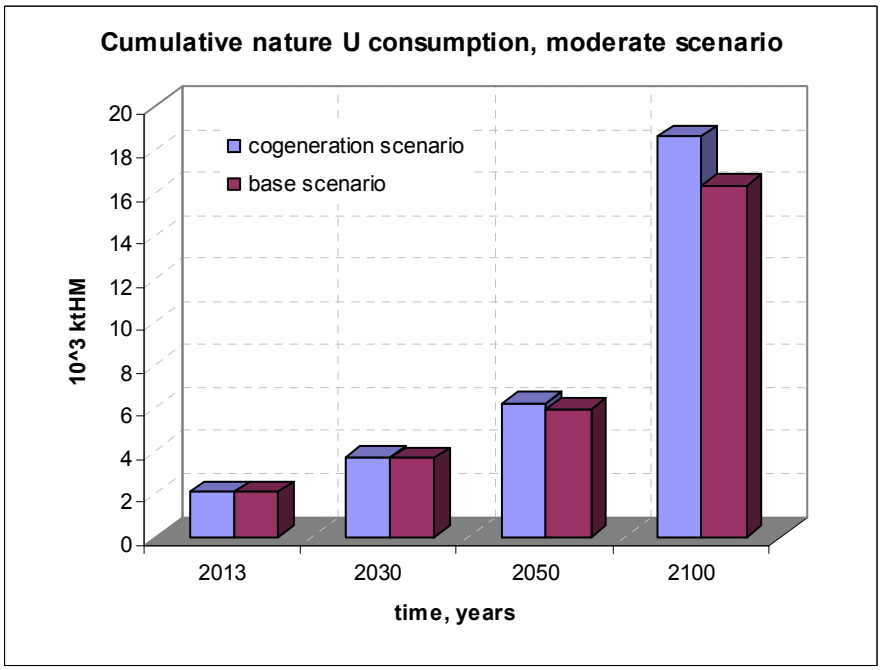


FIG. XXI-41. Cumulative natural U consumption – moderate scenario.

As shown in Fig. XXI-41, natural uranium demand increases by 14 % by the end of the century. Nevertheless, first of all, material balances for the scenario remain acceptable in the framework of the accepted limitations on uranium resources and, second, 1 billion tons of heavy oil is produced which reduces damage for the environment. The difference in natural

uranium consumption could be higher, but it is compensated by more effective fuel use in HTRs. As a result, the difference in accumulated SNF volume is insignificant, Fig. XXI-42.

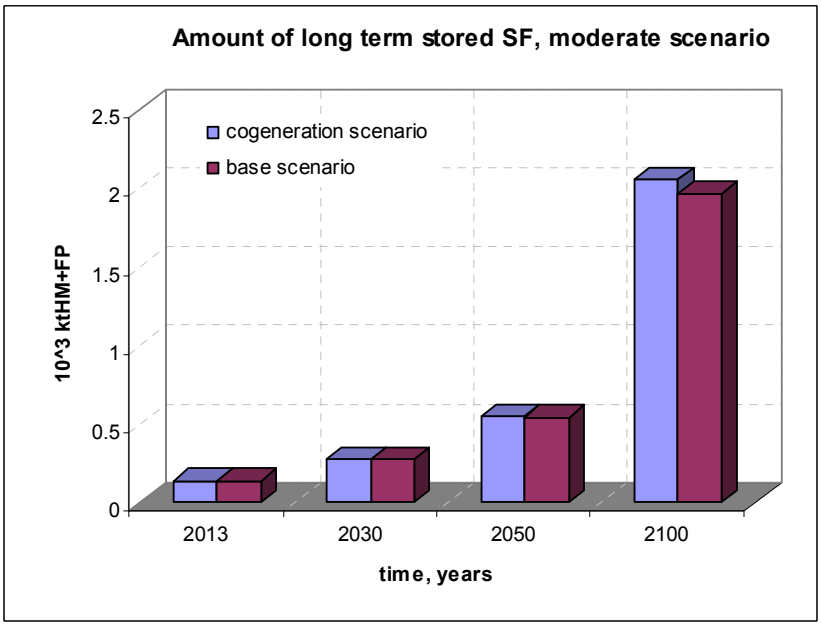


FIG. XXI-42. Amount of long term stored SNF – moderate scenario.

The volume of SNF exceeds the results for non-co-generation scenario by 5%, and the decay heat increases by 8%.

Figure XXI-43 shows the structure of SNF volume for different reactor types.

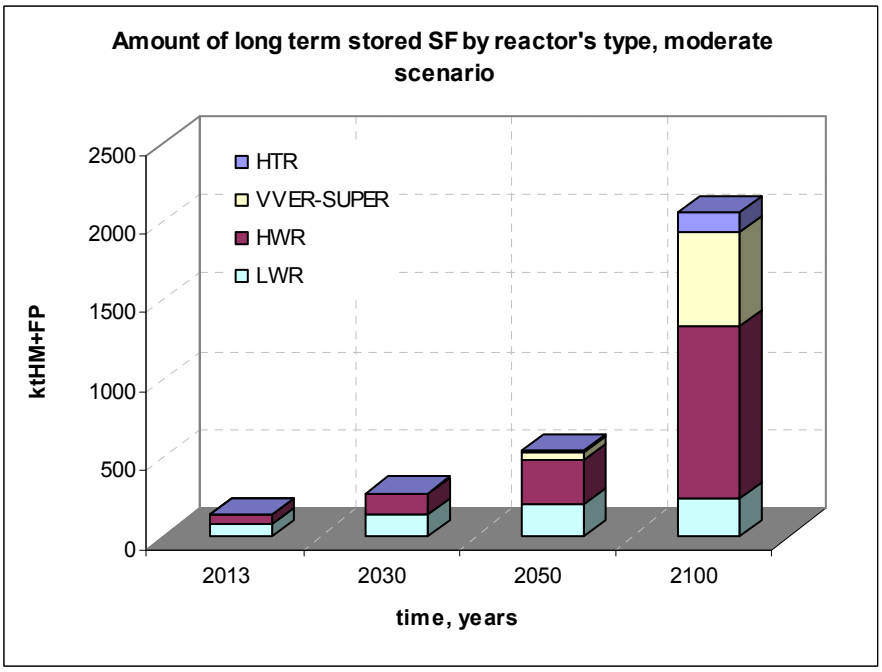


FIG. XXI-43. Amount of long term stored SNF by reactor type – moderate scenario.

HTRs bring slight changes to SNF structure, and most part of the SNF is still from HWRs, although it is reduced from 56% to 53%, see Fig. XXI-44. The VVER-Ss' contribution is reduced similarly from 32% for the basic scenario to 29% for co-generation

scenario. The share of HTRs' decay heat in the structure is more significant and reaches almost 20% because of a high fuel burn-up and, therefore, higher fission products accumulation, see Fig. XXI-44.

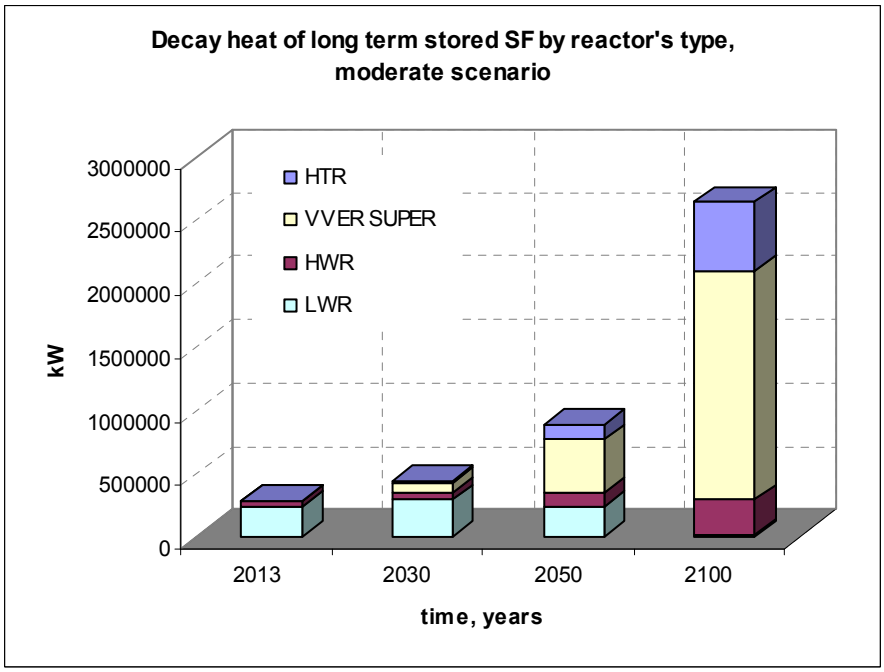


FIG. XXI-44. Decay heat of long term stored SNF by reactor type – moderate scenario.

Thermal power production is 1000 GW for this scenario and almost all of it is spent for heavy oil production. The volumes of productions are presented in Table XXI-11.

TABLE XXI-11. PRODUCTION BALANCE FOR HTRs WITH ANNUAL THERMAL CAPACITY 1000 GW

Area	Value	Unit
Steam	580	kt/h
Heavy oil	116	kt/h
Hydrogen	8.1	kt/h
Electricity	76.7	GW
Petrol	81.3	kt/h
Other fuels and lubricants	34.7	kt/h

XXI-5. CONCLUSION

To create an innovative nuclear energy system that meets the principles of sustainable development one needs to upgrade both thermal reactors and fast reactors. Only when all the reactors comply with the system requirements it will be possible to create a sustainable system. Even for moderate scenario it is necessary to constantly increase uranium production, which means that consumed resources would be doubled even without further development of the system. It is a consequence of logistics laws typical for resource-intensive and inertial technologies like nuclear energy.

Moreover, for guaranteed uranium reserves it is necessary to have a stock with enough uranium for ten years, as it allows avoiding a transition from market to auction with unpredictable price changes. The same is applicable to plutonium stock. But closing of the

nuclear fuel cycle also requires definition of necessary reserves in stock for price stabilization that will depend on group choice and NES structure.

So, apparently, the selected NES structure will be realized at a significantly smaller scale to solve regional problems related to resources provision and sustainability of particular regions, to ensure energy security with SMRs and HTRs.

Further search for sustainable scenarios of the studied variants requires significant enhancement of fuel utilization characteristics for both, thermal and fast reactors.

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APPENDIX I.

TABLE I-1. ISOTOPIC COMPOSITION OF VVER-S REACTOR

Isotope	Initial loading, t	Reload, t	Discharge, t	Full core discharge, t
^{234}U		1.04E-03	4.66E-04	1.86E-03
^{235}U	2.57E+00	8.94E-01	1.16E-01	4.64E-01
^{236}U		0.00E+00	1.25E-01	5.00E-01
^{238}U	7.04E+01	1.74E+01	1.66E+01	6.64E+01
^{237}Np			1.37E-02	5.49E-02
^{238}Pu			6.87E-03	2.75E-02
^{239}Pu			1.11E-01	4.45E-01
^{240}Pu			5.64E-02	2.26E-01
^{241}Pu			3.47E-02	1.39E-01
^{242}Pu			2.04E-02	8.17E-02
^{241}Am			1.08E-03	4.32E-03
^{244}Cm			2.86E-03	6.02E-03
Total FP			1.09E+00	4.68E+00
Total HM	73	18.24994525	1.71E+01	6.83E+01
Total U	73	18.24994525	1.68E+01	6.73E+01
Total Pu	0	0	2.30E-01	9.18E-01
Total MA (Np+Am+Cm)	0	0	1.77E-02	6.53E-02

TABLE I-2. ISOTOPIC COMPOSITION OF KLT-40 REACTOR

Isotope	Initial loading, t	Reload, t	Discharge, t	Full core discharge, t
^{234}U			1.20E-03	1.20E-03
^{235}U	1.79E-01	1.79E-01	8.02E-02	8.02E-02
^{236}U			1.73E-02	1.73E-02
^{238}U	1.09E+00	1.09E+00	1.07E+00	1.07E+00
^{237}Np			9.02E-04	9.02E-04
^{238}Pu			1.70E-04	1.70E-04
^{239}Pu			6.87E-03	6.87E-03
^{240}Pu			2.11E-03	2.11E-03
^{241}Pu			1.29E-03	1.29E-03
^{242}Pu			2.91E-04	2.91E-04
^{241}Am			2.86E-02	2.86E-02
^{244}Cm			4.31E-03	4.31E-03
Total FP			5.52E-02	5.52E-02
Total HM	1.2728	1.2728	1.22E+00	1.22E+00
Total U	1.2728	1.2728	1.17E+00	1.17E+00
Total Pu	0	0	1.07E-02	1.07E-02
Total MA (Np+Am+Cm)	0	0	3.38E-02	3.38E-02

TABLE I-3. ISOTOPIC COMPOSITION OF HTR REACTOR

Isotope	Initial loading, t	Reload, t	Discharge, t	Full core discharge, t
^{234}U			4.91E-02	4.91E-02
^{235}U	4.80E-01	4.80E-01	9.05E-02	9.05E-02
^{236}U			2.43E-03	2.43E-03
^{238}U	5.52E+00	5.52E+00	5.22E+00	5.22E+00
^{237}Np			7.75E-05	7.75E-05
^{238}Pu			2.84E-05	2.84E-05
^{239}Pu			8.45E-02	8.45E-02
^{240}Pu			2.71E-02	2.71E-02
^{241}Pu			1.63E-02	1.63E-02
^{242}Pu			5.42E-03	5.42E-03
^{241}Am			2.58E-09	2.58E-09
^{244}Cm			4.39E-09	4.39E-09
Total FP			5.31E-01	5.31E-01
Total HM	6	6	5.50E+00	5.50E+00
Total U	6	6	5.37E+00	5.37E+00
Total Pu	0	0	1.33E-01	1.33E-01
Total MA (Np+Am+Cm)	0	0	7.75E-05	7.75E-05