ANNEX XVIII.

ALTERNATIVE DEPLOYMENT STRATEGY OF FAST REACTORS - START-UP ON ENRICHED URANIUM FUEL

One of the problems of the current nuclear power industry is small economically feasible resources of natural uranium in terms of use in thermal reactors within existing once-through nuclear fuel cycle (NFC), and the fact that reserves are not equally accessible for different countries. It is determined that large-scale nuclear power capacities operating in once-through NFC cannot be deployed to the level of the organic fuel power plants. This problem defines the scope of the present study.

Addressing the uranium fuelling problem requires modelling of the long-term scenarios of nuclear power deployment in order to predict consequences of various approaches. In terms of valuable resources saving, reduction of the spent nuclear fuel (SNF) accumulation and CO_2 emissions problem resolution before the end of the century, it is promising to create as soon as possible a large-scale nuclear energy system based on a closed NFC.

The concept was developed 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 Nuclear Fuel Cycle (GAINS) [XVIII-1] containing a proposal to build large-scale nuclear capacities by primarily launching fast reactors (FR) fuelled with enriched uranium instead of thermal reactors. It was shown that it is more effective to upload enriched uranium fuel into the FRs with breeding ratio BR>1 and then to recycle its SNF to extract plutonium for further use than to upload low enriched uranium in LWR with BR<1 without further recycling. Such an approach provides accelerated pace of nuclear power deployment without requiring high breeding ratio for these reactors.

Fast reactors start-up on enriched uranium fuel with a subsequent transition to a closed NFC is a new, original concept of large-scale development of fast reactors.

XVIII-1. DESCRIPTION OF GLOBAL NUCLEAR ENERGY DEVELOPMENT SCENARIOS

The global scenarios of three groups of countries are described in detail in the Final Report of the INPRO CP on GAINS [XVIII-1]. In the current study, in the modelling scenarios of transition to sustainable nuclear energy system with fast reactors on enriched uranium, a high case scenario was adopted of up to 5000 GWh by 2100. There is a GAINS scenario modification with enlarged rate of FR commissioning from 2030 to 2050. Considered global scenario refers to an option where the capacities in NG1 are expected to have high growth (from 50% to 65%), calculations are shown in the Table XVIII-1.

TABLE XVIII-1. CAPACITY OF NG1, NG2, NG3 BY YEARS, GW(e)

High NG1 growth (from 50% to 65%)				
Year	NG1	NG2	NG3	Total
2008	149	149	0	298
2030	358	308	33	700
2050	853	510	137	1500
2100	3250	750	1000	5000

Under these conditions, the benefits of FR start-up on enriched uranium are demonstrated most clearly for the following reasons:

- the share of capacity in NG1 (a group of countries that can operate FR) is maximum (3250 GW(e) by 2100);
- in synergistic condition (transfer of half of the thermal reactors' SNF for reprocessing from NG3 to NG1) the share of MOX fuel can be higher due to the plutonium of NG3 thermal reactors and the NG1 natural uranium consumption can be lower;
- NG1 and 50% of NG3 reactors form a single system in the current model.

Thus, the mathematical model consists of NG1 and half of the NG3 capacities (half of NG3 SNF). This means that the scenario works with TR and FR of NG1, as well as with TR of NG3 (see Table XVIII-2). SNF from NG3 is transported to common SNF storage of NF3 and is reprocessed immediately.

TABLE XVIII-2. CAPACITY OF NG1, 50% NG3 BY YEARS, GW(e)

Year	NG1	0.5*NG3	Total
2008	149	0	149
2030	358	17	375
2050	853	68	921
2100	3250	500	3750

There are two scenarios of nuclear energy development by 2100 with different structure of reactor types: LWR with uranium fuel, FR-1200[1] with uranium fuel and FR-1200 with MOX fuel. The total capacity reaches 3750 GW(e) for both scenarios by 2100 as presented in the Table XVIII-2. It is assumed that:

- all SNF is reprocessed immediately;
- cooling time for SNF discharged from LWR is 5 years and from FR is 3 years;
- plutonium and plutonium core areas of reproduction are mixed;
- the regenerated uranium is not used and sent to a separate storage;
- plutonium storage is common for plutonium from reactors of all types. It is produced by reprocessing of thermal and fast reactors SNF.

Prospective scenarios are as follows:

1. The first scenario is based on joint operation of thermal reactors (ALWR-1000 - advanced LWR) with UOX-fuel and fast reactors (FR-1200 with MOX-fuel);
2. In the second scenario commissioning of thermal units stops in 2030. Introduced reactors work until the end of their lifetime. FR-1200 MOX and FR-1200 UOX units provide for replacement of missing capacities.

The capacity of ALWR-1000 reactor (with lifetime of 60 years) reaches 960 GW(e) by 2100 under the scenario 1. To provide the desired total demand (see Table XVIII-2), FR-1200 reactors (with lifetime of 60 years) start to be commissioned in 2021 with total capacity of up to 2790 GW(e) by 2100.

[1] FR-1200 – fast reactor of 1200 MW(e).

Scenario 1 does not appear to be optimal due to the following inherent fundamental flaws:

- long period of thermal reactors mass exploitation entails accelerated depletion of cheap natural uranium reserves;
- full reprocessing of SNF with limited requirements of total fast reactors capacities leads to excessive plutonium stock buildup. The refusal to reprocess irradiated SNF would lead to the large amount of radioactive materials accumulation and will require construction of an ever-increasing number of SNF storages.

Scenario 2 assumes that from 2030 all new installed capacities will be with fast reactors. In case of insufficient amount of plutonium to launch FR-1200 with MOX, the system can put into operation FR-1200 with enriched uranium fuel. In case of FR-1200 with MOX, there would be savings of natural uranium, reducing plutonium stockpiles and the need for new SNF storage facilities.

XVIII-2. REACTOR INPUT DATA

ALWR with high burnup is a common type of existing thermal reactors. Fast reactor performance parameters with MOX fuel are provided in the Table XVIII-3. Characteristics of the Russian-designed BN-1200 sodium fast reactor with MOX fuel in equilibrium conditions were used as an example of a typical fast reactor. The input data for BN-1200 (MOX) was obtained from the Workbook for Higher Education Institutions "Technical physics of fast reactors with sodium coolant" [XVIII-2]. The isotopic composition in the fuel was assumed to be the basic contents of plutonium.

Thermal and fast reactor specifications with enriched uranium fuel are presented in Tables XVIII-4—XVIII-5. Fast reactor (BN-1200 (UOX)) model with enriched uranium fuel was based on a "basic" version of the reactor BN-1200 (MOX).

All the values used in the calculations are average and annual, i.e. the characteristics correspond to reactor operation under normal conditions. This study used a simplified model of fast reactor without core and screen separation modelling.

TABLE XVIII-3. FAST REACTOR SPECIFICATIONS FOR BN−1200 (MOX)

Parameter	Data
Capacity (thermal)	2900 MW(th)
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

The BN−1200 (MOX) lifetime is 60 years.

It was assumed in the calculations that all NFC delays are described by a single value, which is fuel retention time.

TABLE XVIII-4. THERMAL REACTOR SPECIFICATIONS

Reactor type	Burn up, GWyear/ tHM	Fuel enrichment, %	Plutonium concentration in spent fuel, %	Fuel campaign, years	Thermal efficiency, %	Load factor, φ
AVVER	60	4.8	1.26	3	32.6	0.9

The ALWR life time is 60 years.

TABLE XVIII-5. FAST REACTOR SPECIFICATIONS FOR BN−1200 (UOX)

Reactor	FR
Capacity (electric)	1200 MW
Capacity (thermal)	2800 MW
Initial core fuel	40.9 tHM
Annually reloaded mass of fuel	8.18 tHM
Fuel residence time	5x330 days
Average residence time of the whole core	1.0 year
Retention time	3.0 years

The BN−1200 (UOX) life time is 60 years.

The ALWR historical data is presented in the Fig. XVIII-1.

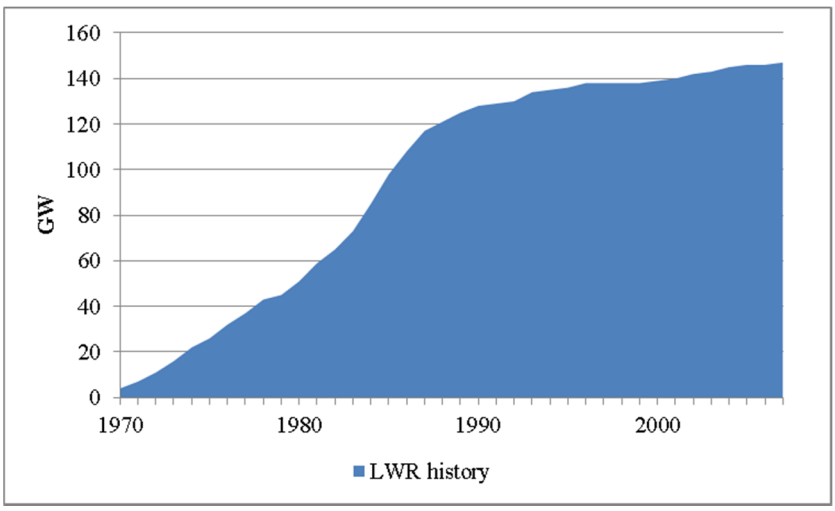

FIG. XVIII-1. The history of thermal reactors commissioning from 1970 to 2010.

XVIII-3. MODELLING FEATURES

The calculations were performed with the help of CYCLE [XVIII-3] software, developed in IPPE for detailed mathematical modelling of the nuclear energy system (material flow balance), and MESSAGE [XVIII-4] software (economic optimization software), both of which illustrate thermal and fast reactor co-operation.

CYCLE was used as primary software for nuclear material flow modelling. This system reflects the main process stages of closed NFC. CYCLE unique feature is detailed modelling of nuclide composition changes at all the NFC stages, including reactors operation. Moreover, this software enables to calculate the characteristics of the material balance, radiation and environmental characteristics of the fuel (heat, activity, radiotoxicity and neutron source) during fuel movement. It can take into account cleaning storage plutonium from americium, components losses and fuel nuclide composition change from the moment of its production to loading into the reactor.

There is an option for NFC describing SNF reprocessing and storages filling with reprocessed uranium, plutonium, neptunium, americium and curium. CYCLE software can model up to three storages with plutonium of different origin and three uranium storages.

The following calculations were made:

- loss factor of the fuel fabrication and reprocessing equals zero;
- plutonium loaded into BN-1200 (MOX) is completely clear of americium;
- the share of ^{235}U in depleted uranium is 0.3%;
- retention time of irradiated fuel assemblies of a fast reactor in cooling pool is 3 years.

XVIII-4. MODELLING RESULTS

Charts of the thermal and fast reactor capacities for scenarios 1 and 2 are shown in Figures XVIII-2 and XVIII-3, respectively.

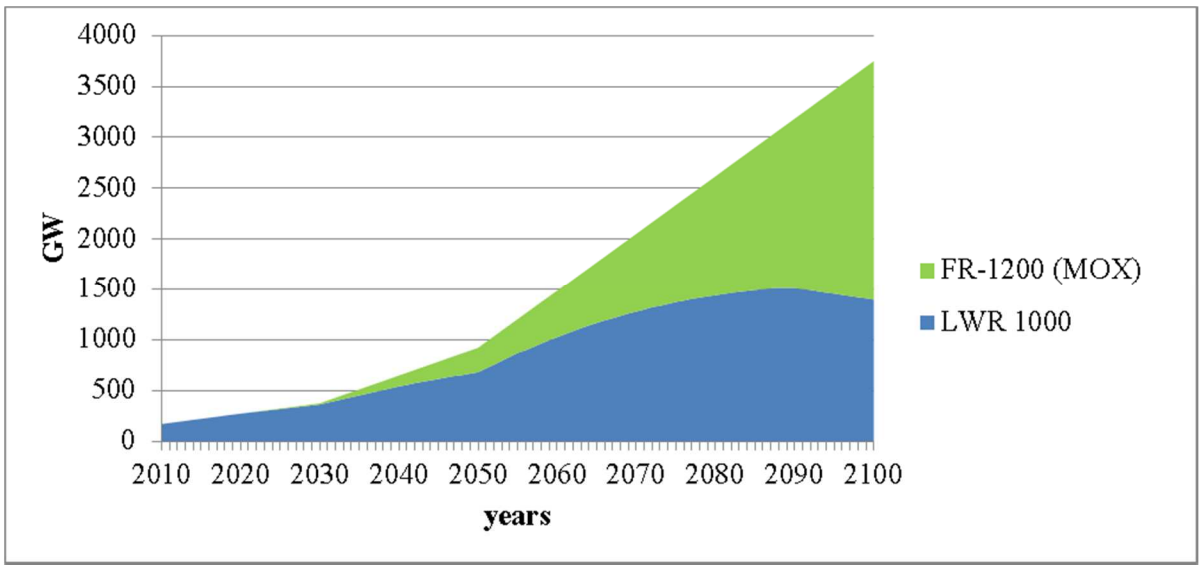

FIG. XVIII-2. Total capacity of thermal and fast reactors in scenario 1.

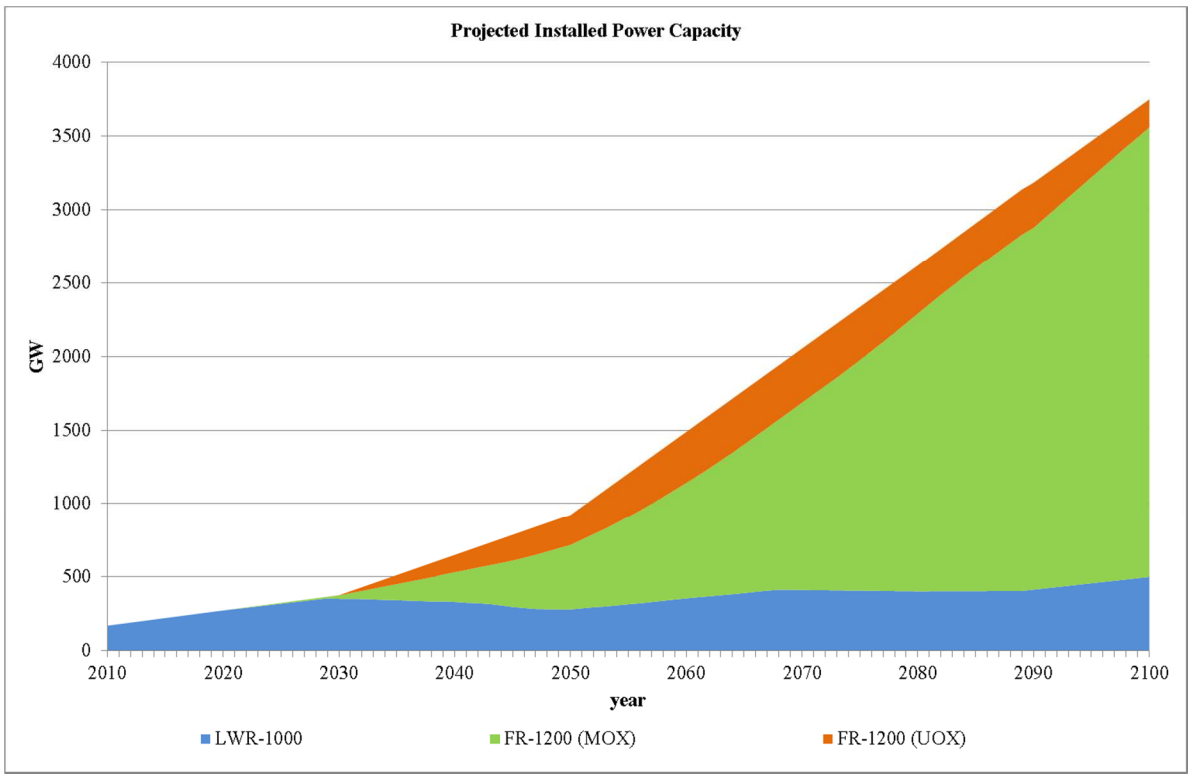

FIG. XVIII-3. Total capacity of thermal and fast reactors in scenario 2.

Figures XVIII-4 and XVIII-5 demonstrate the annual natural uranium consumption for both scenarios. In scenario 1, the total natural uranium consumption equals 11.189 million tons and 1.09 million tons of depleted uranium by 2100. The annual demand for natural uranium is 46 500 tons in 2020, 107 000 tons in 2050 and 142 000 tons in 2100 (the maximum is 177 000 tons in 2076).

In scenario 2, the total natural uranium consumption is 9.91 million tons, depleted uranium consumption is 1.59 million tons by 2100. The annual demand for natural uranium is 46 500 tons in 2020, 216 000 tons in 2050 and 75 700 tons in 2100 (the maximum is 226 000 tons in 2051). Obviously, the second scenario provides 11.4 % economy of natural uranium but leads to a 45.9 % increase of depleted uranium flow. From a comparison of Figures XVIII-4 and XVIII-5, a noticeable spurt in the annual consumption of natural uranium for the second scenario can be observed, when it reaches the maximum value of consumption – 226 000 tons/year in 2076 against 177 000 tons/year in 2051 for the first scenario. This is caused by the BN-1200 (UOX) commissioning.

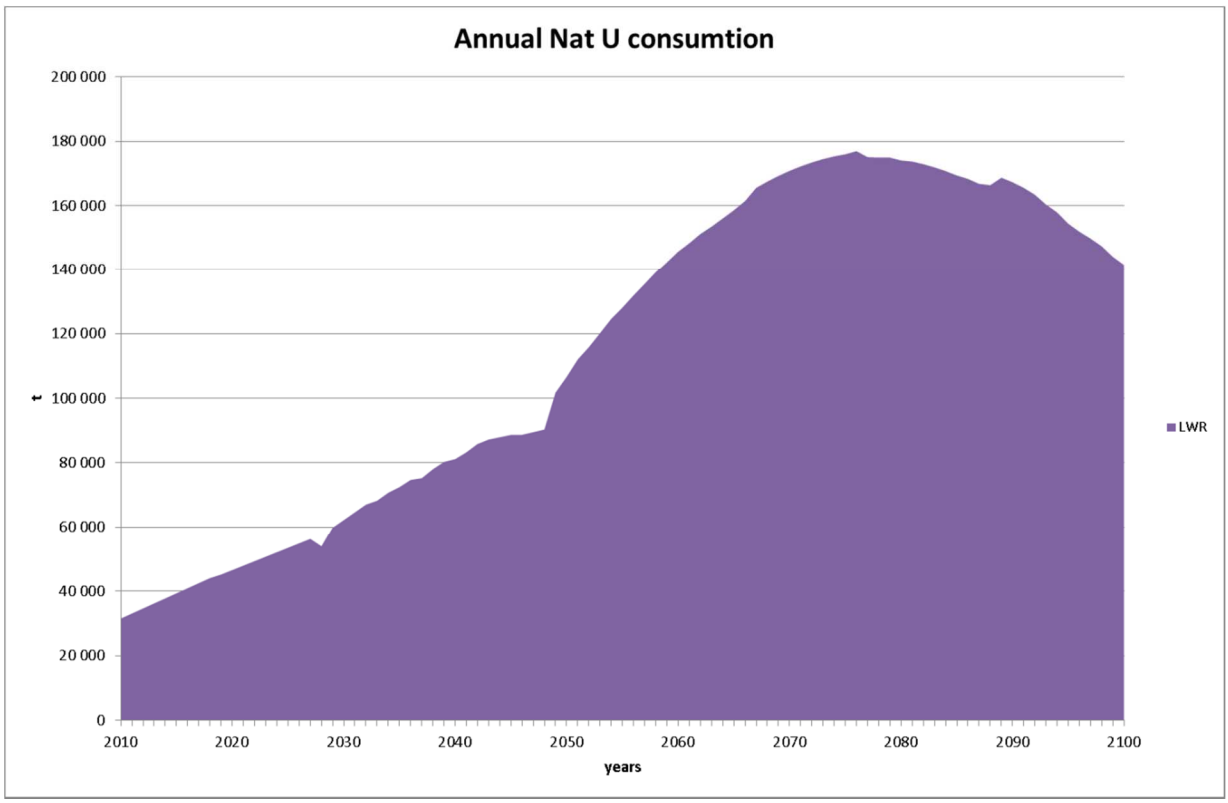

FIG. XVIII-4. Annual natural uranium consumption in scenario 1.

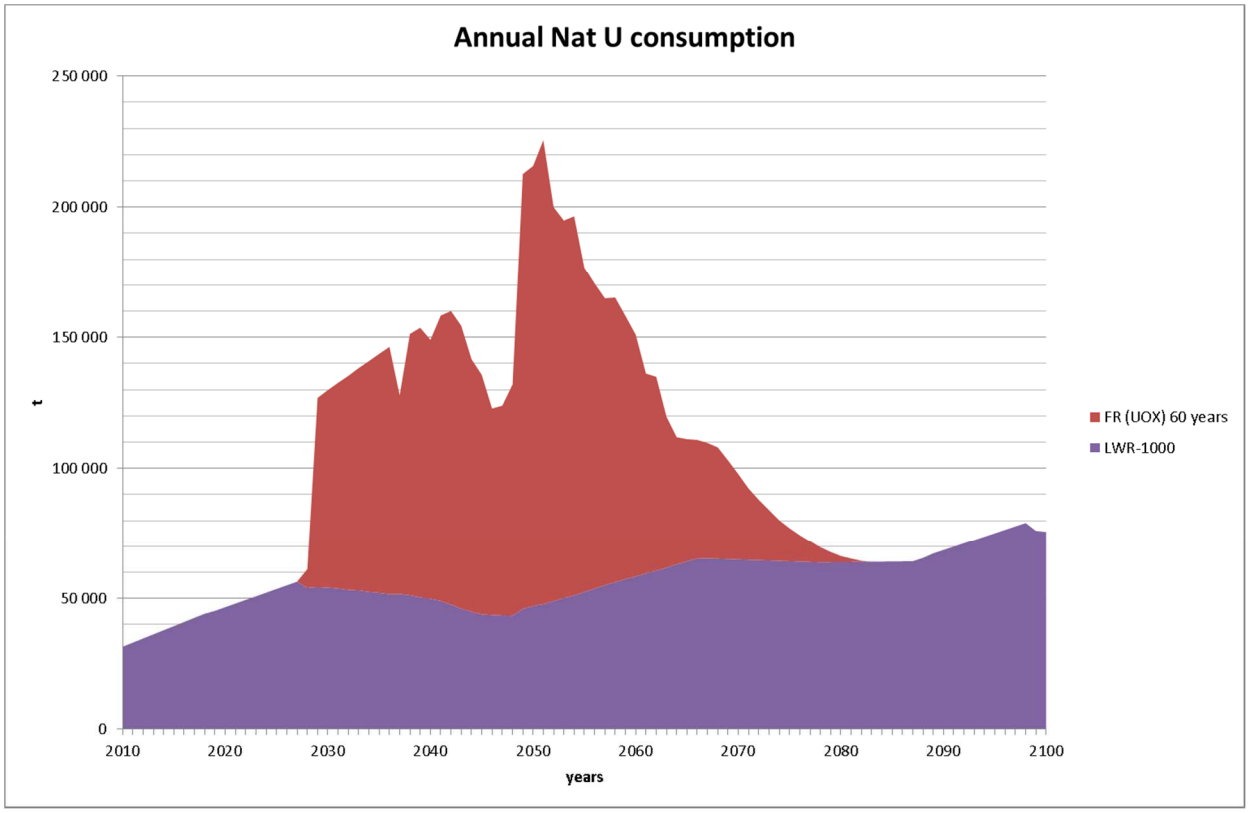

FIG. XVIII-5. Annual natural uranium consumption in scenario 2.

Figures XVIII-6 and XVIII-7 show the demand for SWU versus time.

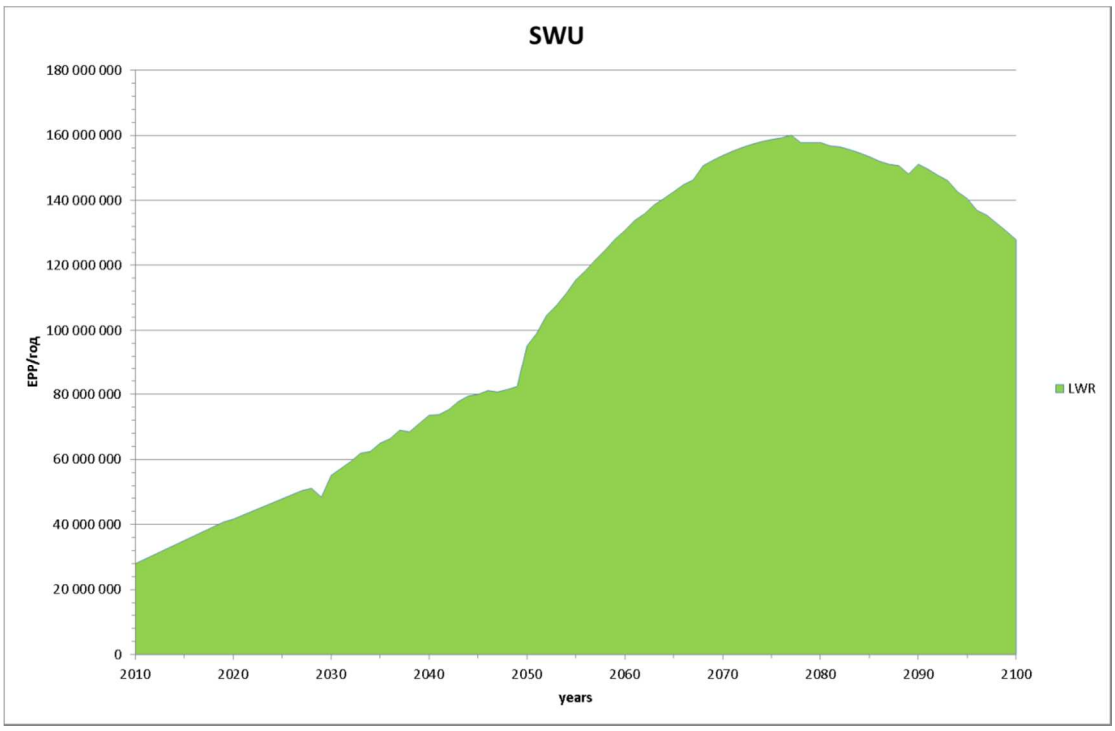

FIG. XVIII-6. SWU demand, scenario 1.

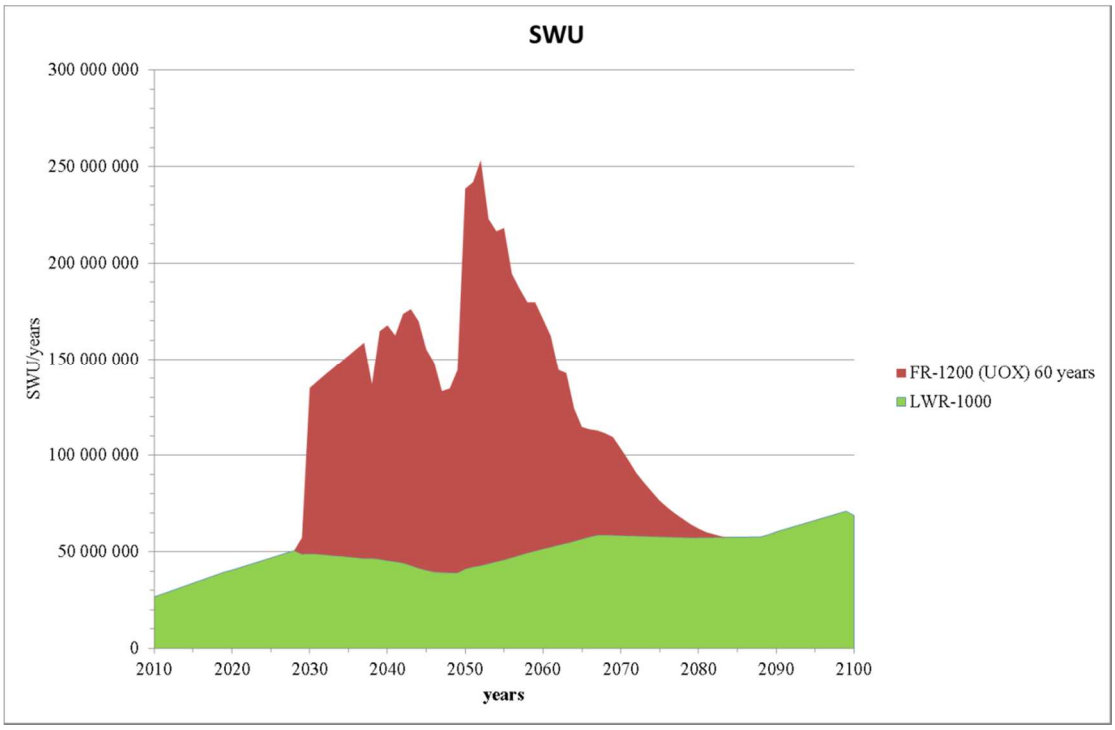

FIG. XVIII-7. SWU demand, scenario 2.

Increased Separated Work Unit (SWU) factory capacities and decreased production requirements by 2080 in the second scenario can be observed, which leads to the lack of SWU demand during reactors' lifetime.

There is a 10% operational plutonium stock in the scenarios. Under such conditions the accumulation of direct use material becomes problematic.

Figures XVIII-8 and XVIII-9 show the amount of plutonium in storage for scenarios 1 and 2, depending on time.

In both scenarios, there is a considerably increasing plutonium amount in storage at the end of the modelling period. In the first scenario, 929 tons of plutonium are accumulated, in the second scenario 3846 tons are produced by 2100.

Figure XVIII-10 shows the annual supply of plutonium transferred to storage from all of the reactors in the second scenario. In 2100, 4130 tons of plutonium are accumulated in storage and 3870 tons of plutonium are merged in the fast reactors. This is approximately four times more than the 10% operational stock of Pu, indicating a lack of optimum plutonium balance in this scenario.

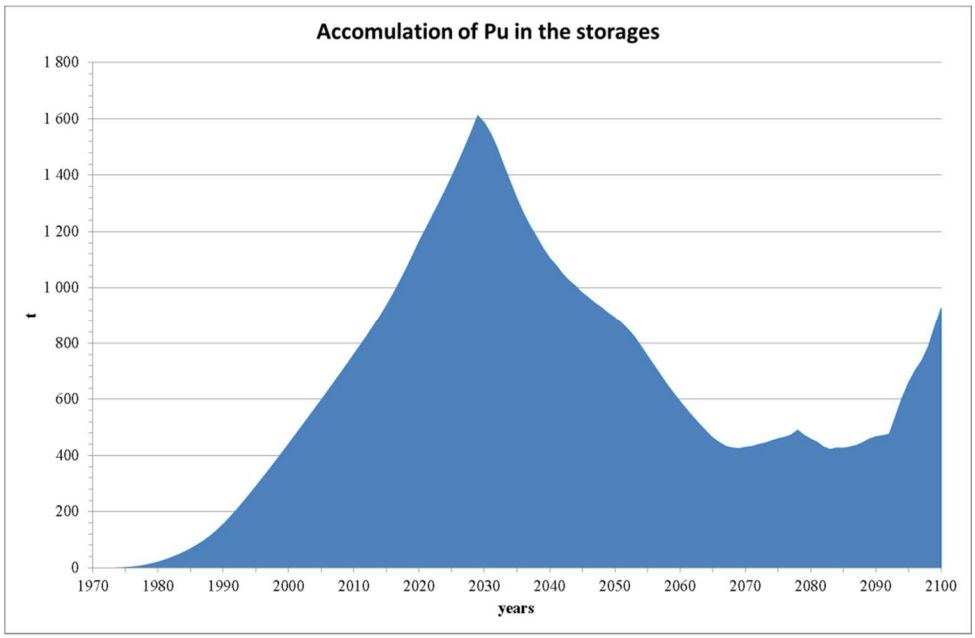

FIG. XVIII-8. Accumulation of plutonium in storage, scenario 1.

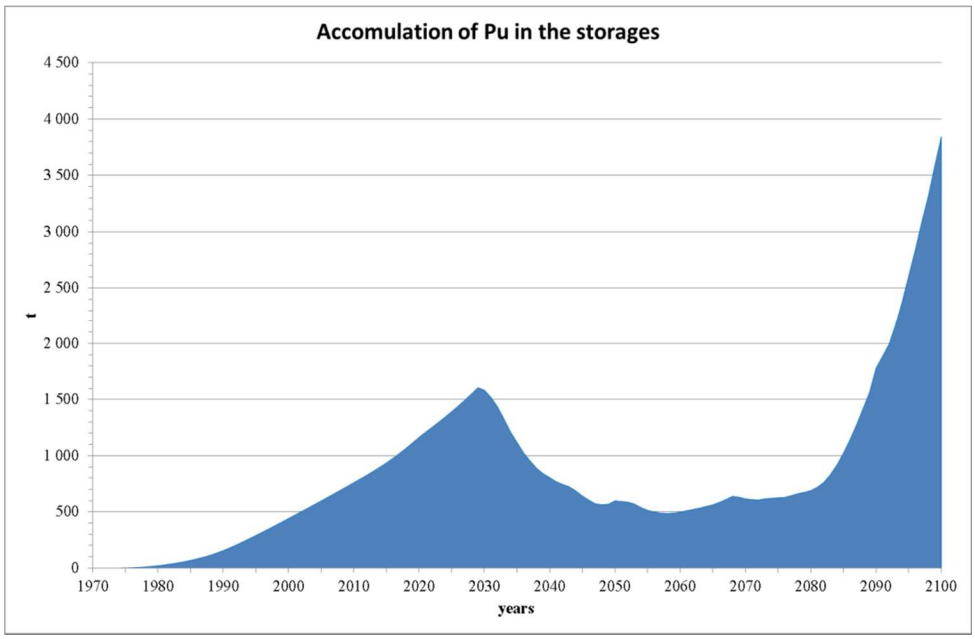

FIG. XVIII-9. Accumulation of plutonium in storage, scenario 2.

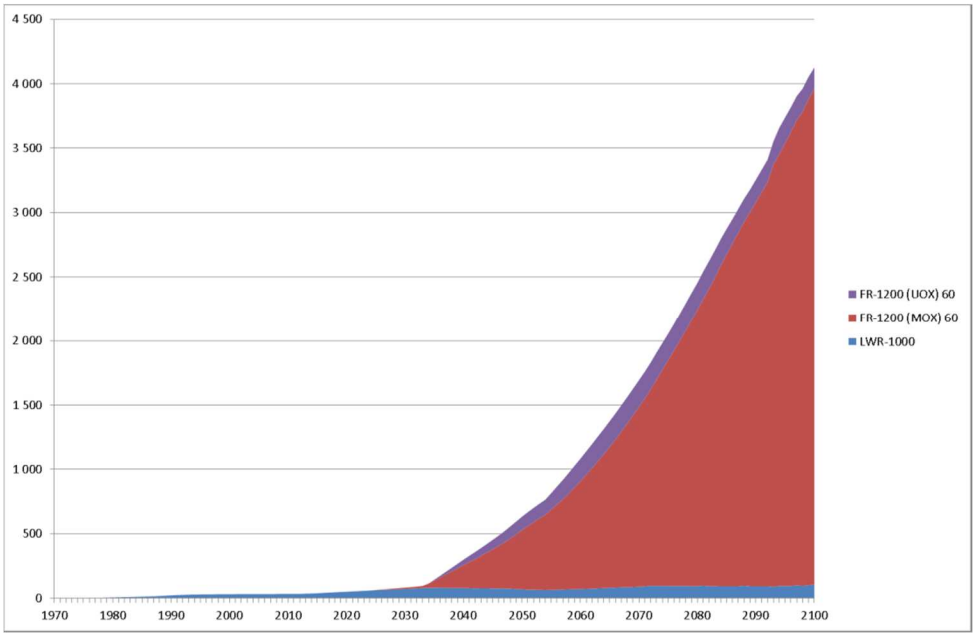

FIG. XVIII-10. Annual supply of plutonium to the storage, scenario 2.

XVIII-5. CYCLE AND MESSAGE MODELLING RESULTS COMPARISON

For global scenarios, which assume a high NG1 growth (50% to 65%) in nuclear energy capacities (see Table XVIII-1), the following results were obtained with MESSAGE software tools.

Figure XVIII-11 shows MESSAGE and CYCLE modelling results of natural uranium consumption comparison during the taken period of time. It is clearly visible that the graphs of the natural uranium consumption almost coincide. The difference at the end of the period does not exceed 2%.

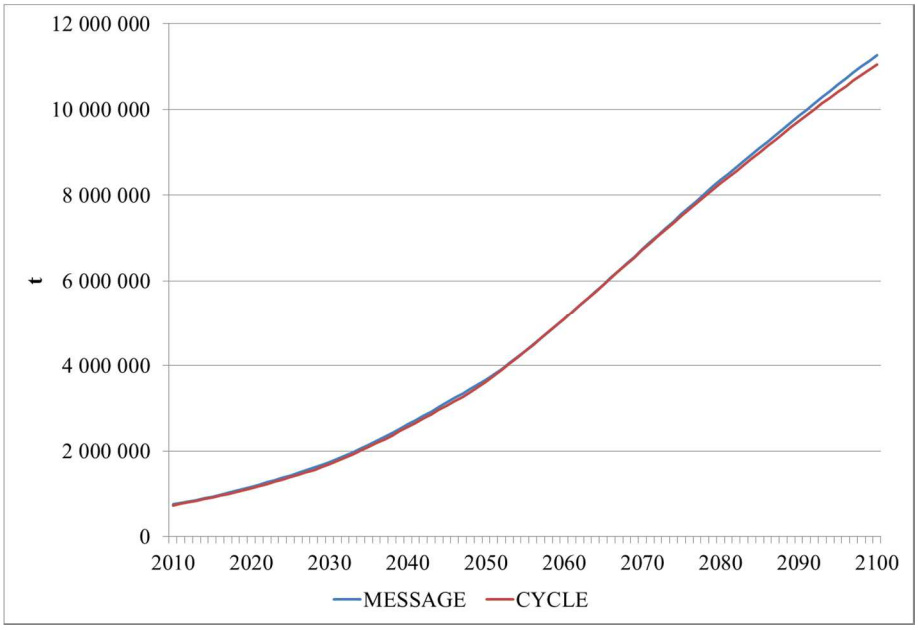

FIG. XVIII-11. Natural uranium consumption; MESSAGE and CYCLE results comparison.

The results for SWU demand, measured with two tools, are quite consistent, see Fig. XVIII-12. From 2010 to 2050, the evolution of the graphs is similar; from 2051 to 2100, the differences in SWU are 4.73% on average.

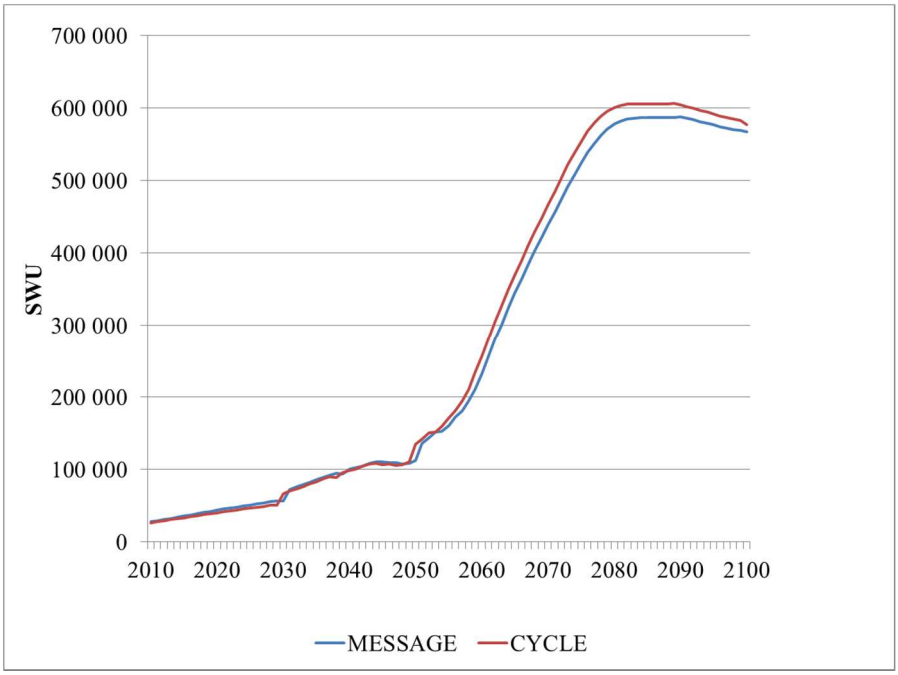

FIG. XVIII-12. SWU demand; MESSAGE and CYCLE results comparison.

The main difference between MESSAGE and CYCLE modelling is in the estimated plutonium amount in storage, which is clearly shown in Fig. XVIII-13. Compared to MESSAGE, CYCLE software is simulating physical transformation of plutonium. From 2030 to 2100 the average difference is 7.3%. The maximum deviation reaches 69.5% in 2081 and the minimum does not exceed 1.0% in 2013.

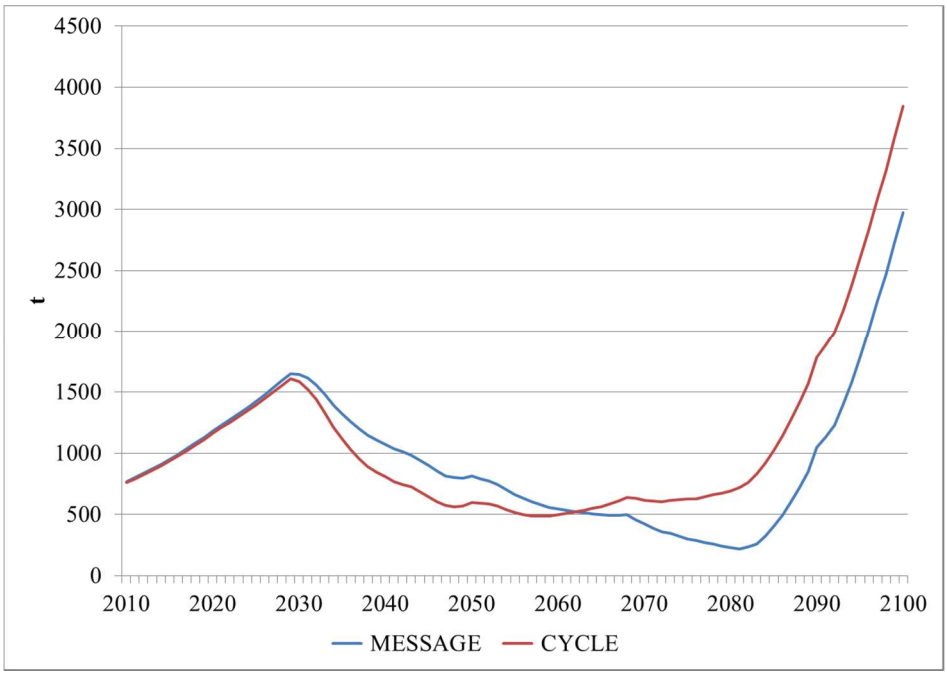

FIG. XVIII-13. Plutonium amount in storage; MESSAGE and CYCLE results comparison.

A low fluctuation data (see Figs XVIII-11—XVIII-13) was obtained through CYCLE output data, then averaged and used as input data for the MESSAGE modelling.

The computation results of the two tools are considerably different in the absence of an averaged input data. The most significant difference can be seen in the parameter for the amount of plutonium in storage. Figure XVIII-14 provides data for plutonium in storage under the global scenario without CYCLE application.

There is a considerable difference in the calculation (over 10%). From 2035 to 2043 the average difference is 8.08%. Since 2044 the mass of plutonium stock, calculated with help of MESSAGE, differs significantly from CYCLE results. In 2100 the difference reaches 200%.

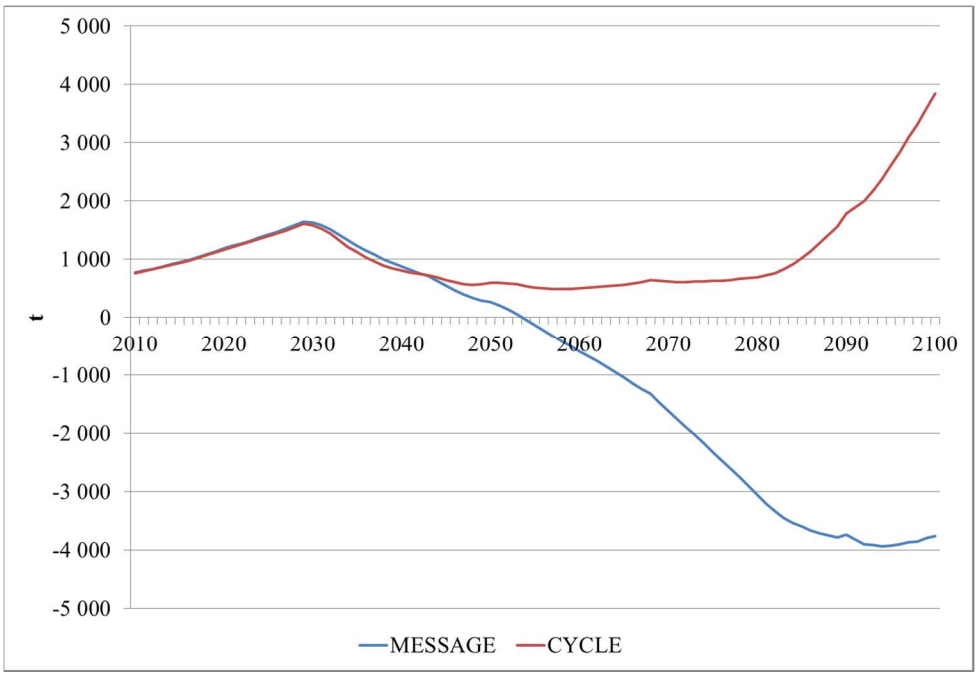

FIG. XVIII-14. Plutonium amount in storage, MESSAGE and CYCLE results comparison (without CYCLE averaged data).

XVIII-6. CONCLUSIONS

The present study considers heterogeneous global scenario for nuclear energy systems based on regional nuclear energy system scenarios with NG1 - NG3 collaborative agreements addressing NFC options. There are two scenarios for comparison. The first one considers use of ALWR and FR (MOX) reactors. The second considers use of ALWR (with no commissioning after 2030), FR (MOX) and FR (UOX). The total demand for electricity is a sum of the NG1 demand and half of the NG3 demand in High NG1 growth (from 50% to 65%) GAINS scenario. There is a closed NFC infrastructure for the NG1 and 50% of NG3 recycling in both scenarios. NG1 and 50% NG3 are considered to be a single nuclear energy system. FR (UOX) consumes enriched natural uranium during the whole lifetime (60 years).

Alternative deployment strategy of fast reactors that are launched with enriched uranium fuel has clear advantages and drawbacks:

1. Saving of natural uranium is about 11% after the 80-year period of modelling.

2. There is strong demand for SWU facilities from 2030 to 2070, with sharp irregularly shaped peaks in 2044 and 2052, and some concern associated with downtime of the enrichment facilities after 2070.
3. From 2080 to 2100, there is a dramatic plutonium accumulation from 500 tons up to 3800 tons in the storages. 400 tons of plutonium is a minimal operational reserve.

There are very few scenarios based on fast reactors start-up with enriched uranium. Considered in this Annex is a test scenario that requires further development and improvement.

REFERENCES TO ANNEX XVIII

[XVIII-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, (2013)

[XVIII-2] V.I. MATVEEV AND YU.S. KHOMYAKOV, Technical physics of fast reactors with sodium coolant, Handbook for Higher Education Institutions, Edited by V.I. Rachkov, Moscow, MEI Publishing House (2012).

[XVIII-3] KAGRAMANYAN V.S., POPLAVSKAYA E.V., KOROBEYNIKOV V.V., KALASHNIKOV A.G., MOSEEV A.L., KOROBITSYN V.E., Analysis of Russian Transition Scenarios to Innovative Nuclear Energy System Based on Thermal and Fast Reactors with Closed Nuclear Fuel, Makuhari Messe, Chiba, Japan December 11-16, 2011.

[XVIII-4] INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS, MESSAGE - Model for Energy Supply Strategy Alternatives and their General Environmental Impact