ANNEX XIX.

# ALTERNATIVE FAST REACTOR DEPLOYMENT SCENARIOS FOR A TRANSITION TO SUSTAINABLE NUCLEAR ENERGY SYSTEM ($^{235}$U LOAD VERSUS U-PU FIRST LOAD)

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) at IAEA has carried out assessment studies on global, regional and country levels based on INRPO methodology for developing a global vision of nuclear energy sustainability for the 21st century [XIX-1–XIX-5]. Particularly, the GAINS project developed a global architecture for sustainable growth of global nuclear energy in the current century. The GAINS project outlined a framework that provides common platform for methodological and dynamic assessment of global NES covering basic assumptions and boundary conditions. The project also performed sample studies and identified potential areas of GAINS framework application for assessment of key scenarios of transition to sustainable future of nuclear energy systems. Global and regional scenario studies [XIX-2] have shown prospects of innovative NES employing closed fuel cycle and containing fast reactors for meeting global and regional nuclear power demands. An INPRO study on thorium fuel cycle [XIX-3] has illustrated that thorium can play an important role in supporting U-Pu based NFC for several scenarios considering high demand growth of world nuclear energy. A joint study [XIX-4] performed assessment of a national NES based on closed nuclear fuel cycle with fast reactors for determining milestones for deployment and establishing frameworks and areas of collaboration for sustainable nuclear energy development.

Although INPRO studies encompass broad areas of technological options for supporting transition to sustainable NES, there are certain possible scenarios that are not considered in these studies. For example, the nuclear reactors used in these studies do not include all reactor design options being developed or considered by Member States, such as high conversion thermal reactors. Similarly, innovative small modular reactor designs with high conversion ratios are at advanced design stages or prototype deployment stage. Such high conversion reactor options can help reduce natural uranium consumption if considered as replacement of conventional LWRs and HWRs, significantly affecting the requirements of FRs or closed nuclear fuel cycle options. Another interesting option is use of FRs with enriched uranium as start-up load followed by utilizing recycled Pu+U+MA from own spent fuel. This option is briefly discussed in [XIX-2]. The present study provides detailed analysis and investigation of the likely impacts of FR introduction using UOX fuel as startup load on the nuclear energy system.

The study employs the framework developed in the GAINS project [XIX-1]. Two growth curves were established for GAINS, as follows: a High case that climbs to 5000 GW(e).year and a Moderate case that climbs to 2500 GW(e).year being flattened after 2100. Each curve has 3 growth periods and follows a linear growth to meet specific level of power generation by the end of respective period:

1) 2009-2030: 600 GW(e).year and 700 GW(e).year growth levels for the moderate and high case, respectively;
2) 2031-2050: 1000 GW(e).year and 1500 GW(e).year growth levels for the moderate and high case, respectively;
3) 2051-2100: 2500 GW(e).year and 5000 GW(e).year for the moderate and high case, respectively.

Four reactor types are considered for the framework base case namely LWR, HWR, FRU (BR~1.0) and FR12 (BR~1.16). It is assumed that FRs can replace LWRs after introduction. HWRs are not replaced by FRs and constitute 6% of total generation capacity. Table XIX-1 and XIX-2 provide general characteristics of considered thermal and fast reactors used in the scenario analysis.

TABLE XIX-1. GENERAL CHARACTERISTICS OF THERMAL REACTORS

| Parameter | LWR | HWR |
|---|---|---|
| Fuel Type | UOX | UOX |
| Electric capacity, MW | 1000 | 600 |
| Thermal efficiency, % | 33 | 30 |
| Load factor, % | 85 | 85 |
| Life time, year | 60 | 60 |
| Core fuel burnup, MWday/kg | 45 | 7 |
| Construction time, years | 5 | 5 |
| Uranium enrichment, % | 4 | 0.711 |
| Cooling time, year | 5 | 5 |
| Reprocessing time, year | 1 | 1 |
| Fuel residence time, effective full power days (EFPD) | 1168 | 292 |
| Mass of the core, tHM | 78.7 | 83.4 |
| Pu content in fresh fuel | - | - |

TABLE XIX-2. GENERAL CHARACTERISTICS OF FAST REACTORS

| Parameter | FRU | | FR (BR~1.16) | |
|---|---|---|---|---|
| Fuel type | Enriched U | MOX-depleted U | MOX-depleted U | |
| Electric capacity, MW | 1000 | | 500 | |
| Thermal efficiency, % | 43.5 | | 40 | |
| Load factor, % | 85 | | 85 | |
| Life time, year | 60 | | 60 | |
| Core fuel burn-up, MWday/kg | 72.8 | | 76.5 | |
| Construction time, years | 5 | | 5 | |
| Uranium enrichment, % | 11.8 | | - | |
| Cooling time, years | 2 | | 2 | |
| Reprocessing time, years | 1 | | 1 | |
| | core | core | core | blanket (depleted U) |
| Fuel residence time, EFPD | 1800 | | 540 | 762 |
| Mass of the core, tHM | 75 | 56.9 | 8.1 | 19.2 |
| Pu content in fresh fuel | - | 0.114 | 0.24 | - |

Following the GAINS approach, several assumptions were implied on the reactor and fuel cycle features, namely:

- Uranium enrichment tails assay of 0.2%;
- Zero loss factor for fuel reprocessing;
- Temporary storage of SNF from HWRs;
- Unlimited uranium supplies.

FR with enriched uranium first loading (FRU) was inroduced into the basic fuel cycle system of GAINS as shown in Fig. XIX-1.

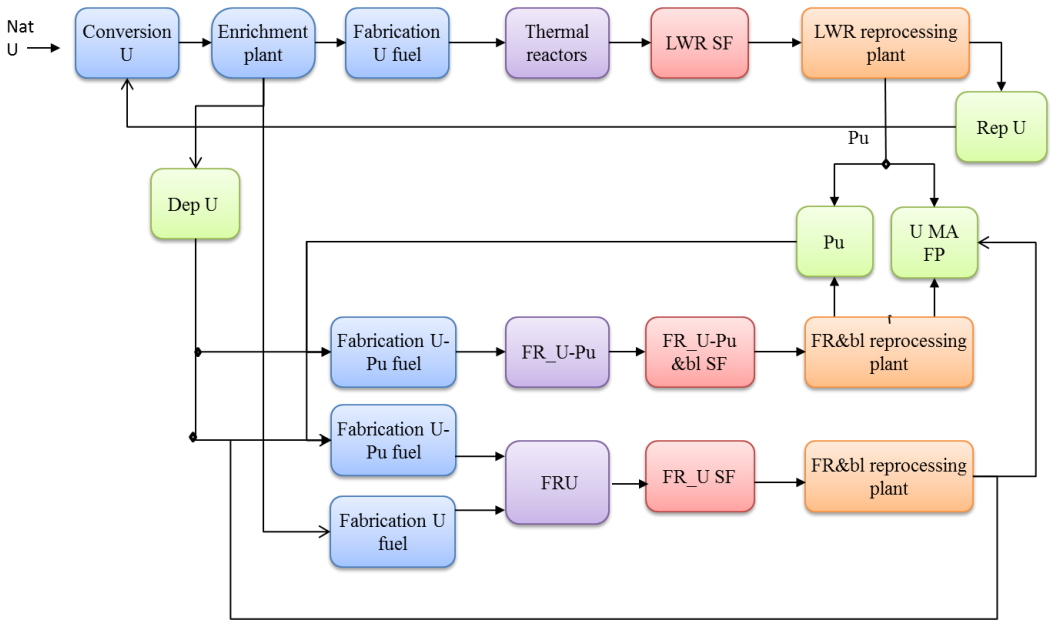


*FIG. XIX-1. Fuel cycle system of BAU with FR scenario.*

The FRU introduction in the global NES is analyzed using MESSAGE code present in the IAEA's package of NES modelling tools. Formulation and evaluation of alternative energy resource strategies is performed with MESSAGE code. The MESSAGE is an optimization tool [XIX-6] that performs energy production and consumption balances and provides forecast of an energy system development along with cost analysis for the whole system. The MESSAGE code was recently updated [XIX-6 to XIX-8] to simulate extended details of a nuclear power system to desired level of complexity. NES can be modelled at each component level, such as fuel startup loading and final unloading, spent fuel cooling time, process lag and lead times, process losses etc.

Fig. XIX-2 to Fig. XIX-5 present comparison of key characteristics of considered reactor types for detailed understanding of scenario simulation. Total natural uranium consumption for first load and total annual reload over the life of reactor is compared in Fig. XIX-2. FRU show highest consumption of uranium for the first core loading with relatively small natural uranium consumption for refueling over first three years and then convert to utilizing own recycled fuel (U-Pu-MA). So the initial stages of FRU deployment may show slightly higher natural uranium consumption for shorter period. Nevertheless, LWRs have the highest total natural uranium consumption during lifetime and FRU has the lowest uranium consumption in the form of enriched uranium. Therefore, replacing LWRs by FRs can lead to potential saving of natural uranium resources. Similar trends are shown by the Fig. XIX-3 in terms of total SWU requirements.

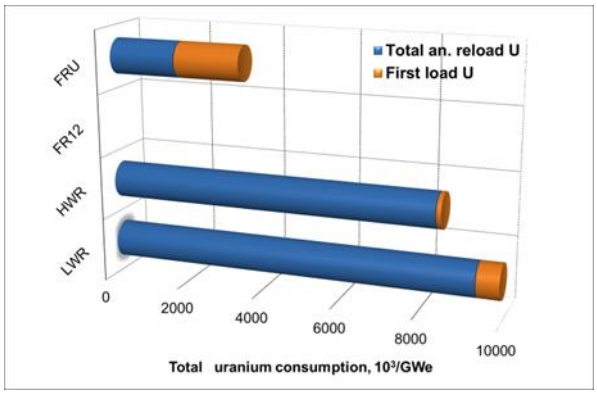


*FIG. XIX-2. Total uranium consumption.*

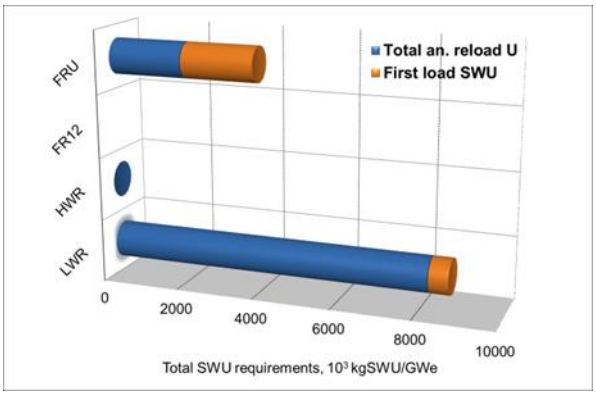


*FIG. XIX-3. Total SWU requirements.*

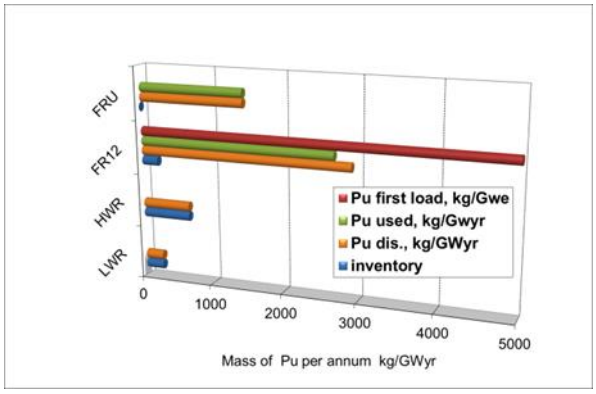


*FIG. XIX-4.Mass of Pu per annum.*

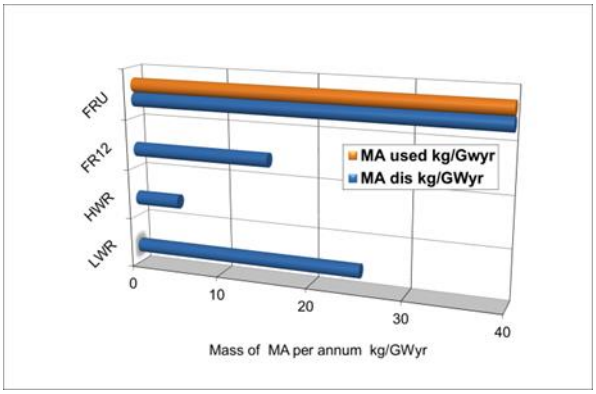


*FIG. XIX-5. Mass of MA per annum.*

Fig. XIX-4 shows the plutonium consumption data including the first load and production or accumulation in the spent fuel. It also shows comparison of Pu 'inventory', which is a difference between production and consumption of plutonium for the typical reactor type. Fig. XIX-5 shows a comparison of MA production over the life of reactors.

Although FRU produces the highest amount of mass, it consumes all of it without MA accumulation. One would expect a reduction of long-lived radioactive waste inventories by diminishing the accumulation of minor actinides in scenarios with FRUs. Those reactor characteristics and the share of these different reactors in NES are the main cause for the results produced within the scenario studies presented later in this study. There are constraints imposed by the GAINS framework on total power production rate of FRs by 2030 and 2050, with objectives in high growth case to have total FR generation rate of 10 GW(e).year in 2030 and a total of 400 GW(e).year in 2050. The GAINS framework also puts constraint on total plutonium inventory in the SNF storage to be maintained close to zero. FRs introduction rate after 2050 is not constrained by the capacity, but rather limited by plutonium availability and overall growth rate of the nuclear energy system. It is also assumed in GAINS framework that there is no limit on fuel cycle infrastructure such as capacities of uranium mining, conversion, uranium enrichment, fuel fabrication, long term storage for spent fuel, interim storage for separated nuclear materials (Pu, MA, FP etc.), SNF reprocessing and final geological disposal facilities.

GAINS sensitivity studies explored a limitation on reprocessing capacity because a reprocessing plant, compared to other elements of the NFC, can be considered as the most complex and expensive facility, depending on the unit size. Such studies performed

comparison of Pu availability under two assumptions on reprocessing, being reprocessing on demand and industrial reprocessing. For the reprocessing on demand assumption, reprocessing takes place without any capacity limitation and depend only on Pu demand and spent fuel availability. Under industrial reprocessing assumption, the reprocessing capacity is limited to 0.850 ktHM/year, corresponding to UP2 or UP3 plant capacities at La Hague. Thus, annual plutonium production depends on availability of both spent fuel and reprocessing plant capacity. The analysis has shown that available industrial reprocessing capacity significantly lacks the plutonium production to satisfy the FR introduction rate. Limited reprocessing capacity will reduce the introduction rate of FRs, which must be considered in efficient planning of long term global transition scenario towards fast reactors.

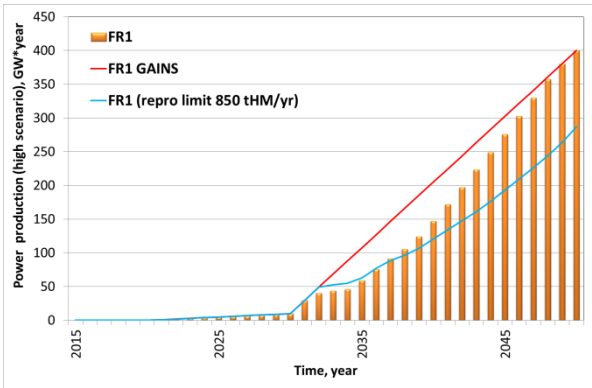


*FIG. XIX-6. FR power production growth.*

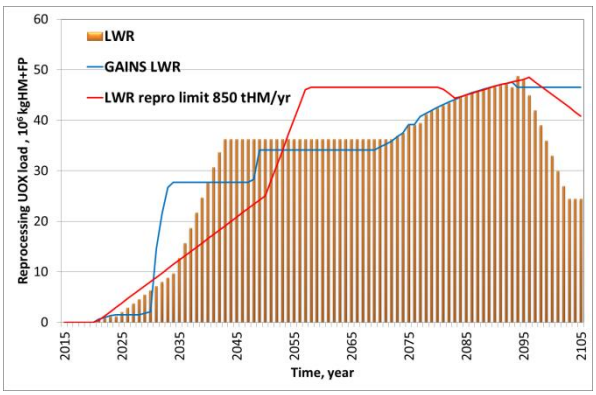


*FIG. XIX-7. Reprocessing rates for UOX fuel.*

The study further investigates the impact of limiting LWR reprocessing capacity on possible deployment of FRs. Fig XIX-6 and Fig XIX-7 show the curves for power production growth demand of FRs as identified by GAINS (linearly growing to 400 GW(e).year by 2050) and related demand reprocessing load. With unlimited separation capacity, it results in significant reprocessing requirements for a very short period of about 1-3 years in 2030 and 2050 for the first FR fuelling. Fast reactors require operational time of 3 years prior to start using plutonium reprocessed from their own spent fuel. Many reprocessing facilities cannot be built in a limited duration of few years due to economic constraints. Fig XIX_6 and Fig XIX-7 also show that power production growth rate of 400 GW(e).year for FRs can be achieved if introduction of new reprocessing capacities is limited to 850 tHM/year of LWR SNF till 2050 and up to 3000 tHM/year of LWR SNF afterwards. Whereas, limiting new LWR reprocessing capacity introduction to 850 tHM/year results in only 300 GW(e).year power production capacity realization. Hence the limitations in reprocessing capacity pose a considerable limit on the FR deployment. If the reprocessing capacity introduction limit is elevated to 3000 t/year of SNF after 2035, LWR spent fuel reprocessing can be increased and 400 GW(e).year FR power growth can be achieved by 2050. However, the demand will not be met by linear growth of FRs in this case. This issue can be overcome by using enriched uranium as first fuel loading in FRs. It should be noted that the option with enriched uranium as the first core load of the fast reactor fleet has both benefits and disadvantages, as it would lower the demand for reprocessing capacity but would require more enrichment capacity. Therefore, selection of this option would be subject to comprehensive assessment of whole indicators developed within GAINS framework.

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This study employs the GAINS framework for assessing impact of different reactor types on infrastructure requirements of nuclear fuel cycle over time. The study considered

sodium and lead cooled fast reactors, first loaded with enriched uranium and subsequently shifting to their own plutonium based reprocessed fuel subsequently. The study is aimed at identifying the prospects and limitations of deployment strategies of different FRs and their combinations. The sensitivity of fast reactor shares is evaluated towards different key indicators of nuclear energy system. Following possible options with mentioned FR shares are evaluated in the current study:

- BAU – Once-through NFC using conventional LWRs and HWRs;
- FR12_00%/FRU_100% - FR12 at 0% and FRU at 100% share of total FR demand;
- FR12_25%/FRU_75% - FR12 at 25% and FRU at 75% share of total FR demand;
- FR12_50%/ FRU_50% - Both FR12 and FRU with 50% share of total FR demand;
- FR12_75%/ FRU_25%- FR12 at 75% and FRU at 25% share of total FR demand;
- FR12_100%/ FRU_00%- FR12 at 100% and FRU at 0% share of total FR demand.

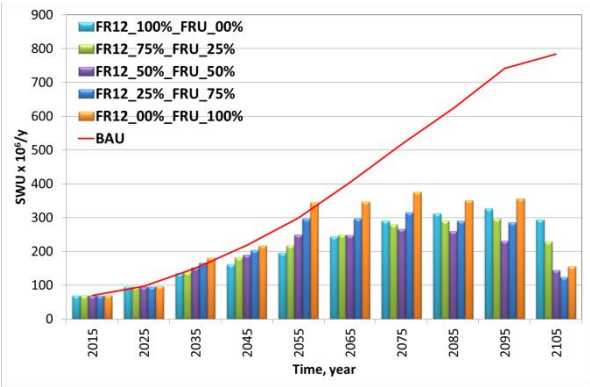


*FIG. XIX-8. FR power production growth.*

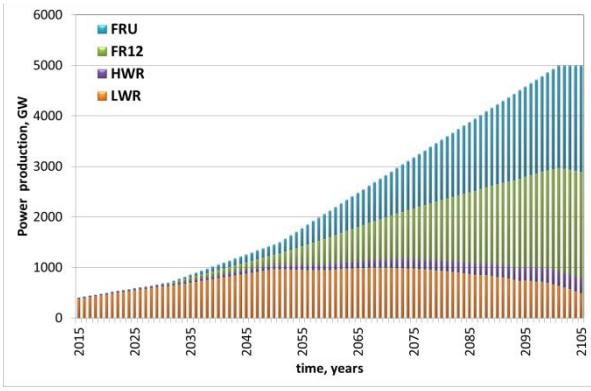


*FIG. XIX-9. Power production growth (FRUs are 50% of the FR power production growth).*

Fig. XIX-8 shows the FR power production growth for different shares of FR types varying from 0% to 100%. Fig. XIX-9 shows overall global power production growth for a case of both FRU and FR12 shares at 50% of FR nuclear power demand. Total FR demand is set initially at 400 GW(e).year by 2050 and at maximum possible FR introduction rate afterwards.

Different FR share options are analyzed and compared with the BAU option for the key indicators of NES such as cumulative natural uranium utilization, SWU requirements, LWR SNF reprocessing requirements, SNF accumulation in dry storage facilities, reprocessed fission products and MA stocks, PU and MA accumulation in long term SNF storage facilities.

Fig. XIX-10 and Fig. XIX-11 show cumulative natural uranium consumption for the considered options and comparative performance of these options to the BAU scenario, respectively.

All options of FR shares show similar saving of natural uranium in the long term perspective, with option of FR12_50%/ FRU_50% performing slightly better. However, completely different trends are observed in short and medium terms. The highest natural uranium consumption is observed with the FR12_00%/ FRU_100% option until 2060 and this trend is even higher than the BAU option rising 5% above it from 2035 and 2040. The lowest natural uranium consumption is observed with the FR12_100%/ FRU_00% option until 2070. The FR12_50%/ FRU_50% option shows intermediate natural U consumption in the medium term lying close to the FR12_100%/ FRU_00% option, which is justified since there are

significant requirements of natural uranium for first enriched uranium core loading of FRU reactors as shown by Fig. XIX-2.

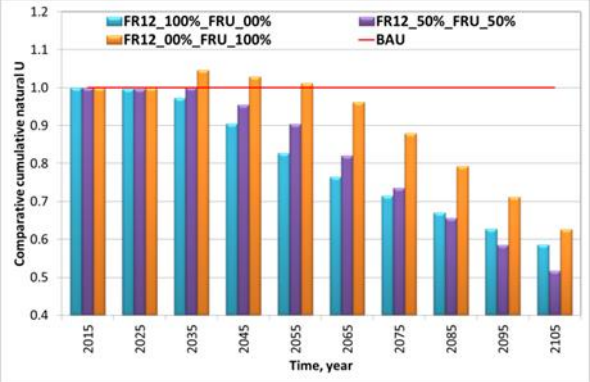


*FIG. XIX-10. Cumulative natural U consumption.*

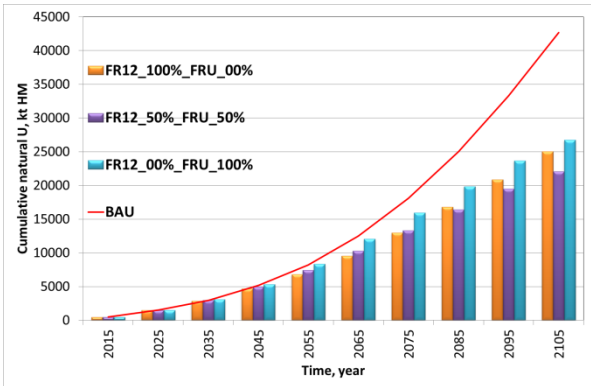


*FIG. XIX-11. Comparative cumulative natural U consumption.*

Annual separation work requirements calculated for different FR share options are shown in Fig. XIX-12. The SWU requirements for BAU case are comparable with other FR share options in the short (until 2030) and medium (until 2050) terms, but considerably higher than all FR options in the long term rising to 800 kt SWU/year by 2100. Two relatively short lived steep SWU growth trends are observed for the FRU options around 2030 and 2050 resulting from the increase in capacity growth rate of FRUs. Most noticeable rise in SWU requirements from 220 to 350 kt SWU/year is observed for the FR12_00%/FRU_100% option in 2050, but straightens afterwards till the end of century. Most feasible results are obtained from the option of FR12_50%/FRU_50% which shows nominal growth in 2050 and minimal level of SWU requirements for the medium and long terms, thus being the optimum choice among all FR share options.

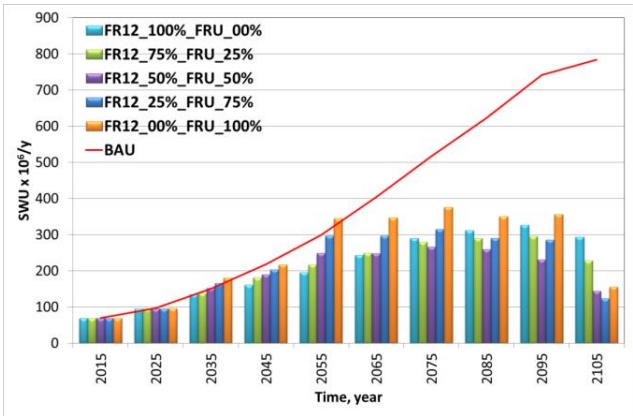


*FIG. XIX-12. SWU requirement.*

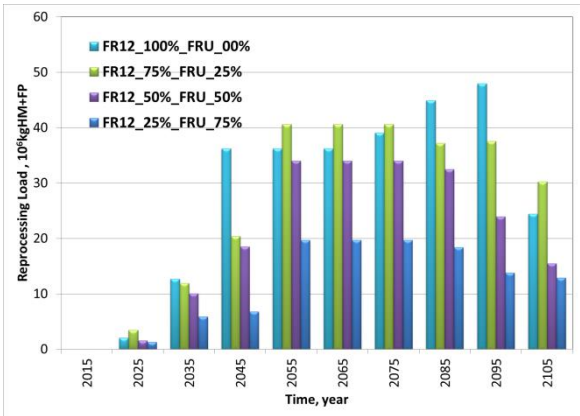


*FIG. XIX-13. LWR reprocessing capacities.*

Fig. XIX-13 shows the annual reprocessing load of LWR spent fuel for the considered options. The FR12_100%/FRU_00% option involves reprocessing capacity requirement up to 34 ktHM for satisfying the FR deployment target of 400 GW(e).year by 2050, with rate of new reprocessing capacity requirement being up to 0.850 ktHM/year before 2035 and 3.0 ktHM/year after 2035. The FR12_75%/FRU_25% option shows further reduction in

reprocessing capacity requirement and addition rate of reprocessing capacity. There is no LWR reprocessing capacity requirement for the option of FR12_00%/FRU_100% since FRU utilize own recycled spent fuel only.

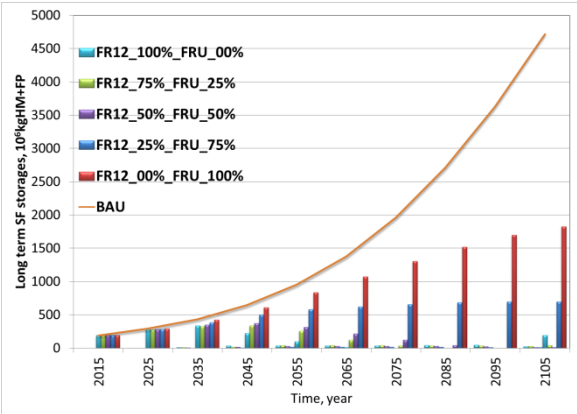


*FIG. XIX-14. LWR long-term storages.*

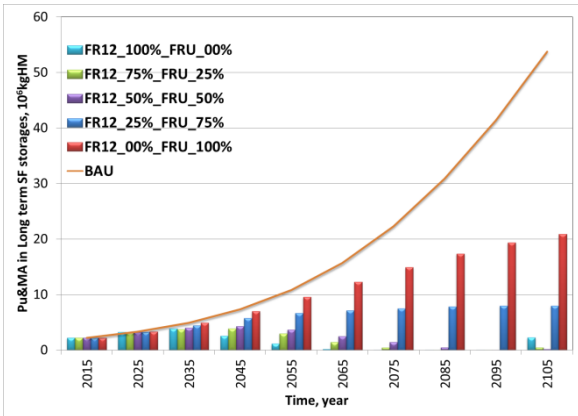


*FIG. XIX-15. Pu and MA accumulation in LWR long-term storages.*

The accumulation of LWR spent fuel in long term storage facilities is shown in Fig. XIX-14 and accumulation of Pu and MA in this spent fuel is shown in Fig. XIX-15 for the considered FR share options. The BAU option employing thermal reactors based once-through fuel cycle shows extensive LWR SNF accumulation reaching nearly 4500 kt by 2100. For the FR12_00%/FRU_100% option, spent fuel accumulation rate drops by a factor of 2.3 due to reduced LWR share in the nuclear energy mix, but the accumulation is still a considerable issue. The fast reactor introduction options with FRU share up to 50% operating in closed fuel cycle show significant reduction in LWR SNF accumulation, with accumulation approaching zero for FRU share of 0%, 25% and 50% in 2065, 2080 and 2090, respectively. Since HWR SNF is not recycled, its inventory in storages increases continuously. The FR spent fuel is never accumulated in the long-term storages since it is reprocessed as soon as it gets cooled in temporary storages.

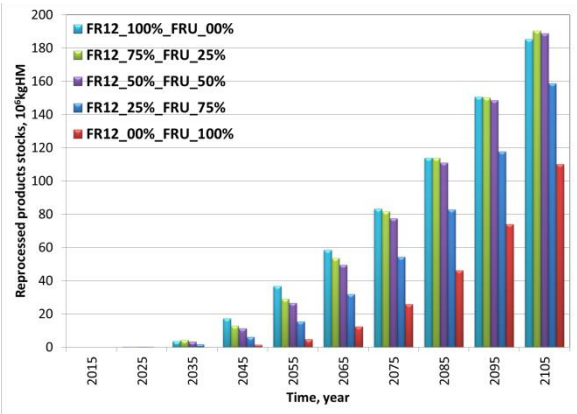


*FIG. XIX-16. Reprocessed FP stocks.*

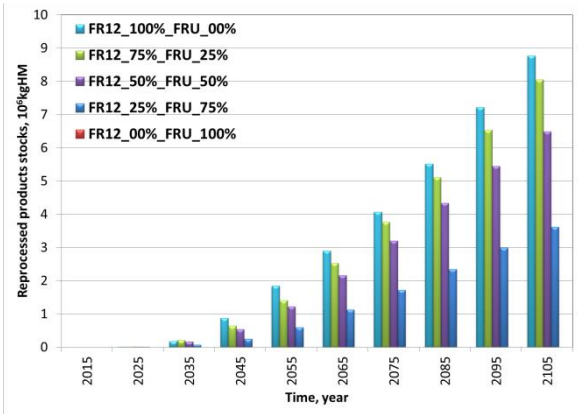


*FIG. XIX-17. Reprocessed MA stocks.*

Similar trends are obtained for the Pu and MA stocks in the LWR spent fuel present in long term storages. Pu inventory in long term storage facilities needs significant consideration and must be minimized since it poses nuclear waste hazard due to long-lived radiotoxic

properties and potential proliferation risk being a direct use material in nuclear explosive devices.

Fig. XIX-16 and Fig. XIX-17 show reprocessed fission product stocks and minor actinide stocks for different FR share options. The options with FRU share less than 50% show reduced amount of reprocessed FP and MA stocks, resulting in increased accumulation of FP and MA in non-repocessed LWR SNF present in long term storages since all of LWR spent fuel is not reporcessed in such cases.

## XIX-1. SUMMARY OF RESULTS FOR THE COMPARISON OF THE OPTIONS UNDER CONSIDERATION

The study considered six different FR share options under high demand scenario of nuclear power for analysis. Introduction of an FRU which uses enriched uranium as first load and subsequently shifts to utilize its own recycled fuel into a nuclear energy mix which is based on UOX-fuel based LWR, HWR and MOX-fuel based FR has both advantages and disadvantages. The sensitivity analysis are performed for studying the impact of different fast reactor shares on key indicators of nuclear energy system, such as natural uranium consumption, spent fuel accumulation, reprocessed products inventories, requirements of enrichment and reprocessing capacities.

The more share of FRU is added, the more likely a fleet of fast reactors can be deployed since there are reasonable requirements for available plutonium that will limit the overall FR growth rate. The fleet of fast reactors in FR12_00%/FRU_100% case could be increased by a factor 1.5150% as compared to the FR12_100%/FRU_00% case by the end of century. In the short and medium terms, FRU introduction allows the deployment of the high scenario FR programme under LWR reprocessing capacity limitations. Using enriched uranium for first fuel loading of FR reduces the reprocessing capacity requirements since it does not require reprocessing.

All FR options show considerable natural uranium savings when compared to the BAU case by 2100 in the long term perspective. However, increasing the share of FRU has negative impact on natural uranium consumption in medium and short terms, caused by significant demand of enriched uranium for first few years of FRU operation on UOX-fuel. Hence, a combination of FRU and FR12 at 50%/50% share delivers a compromised intermediate solution for all time segments in terms of natural uranium consumption.

The enrichment capacity requirement is increased by using enriched uranium for first fuel loading in FRU. The increase in growth rate of FRU around 2030 and 2050 results in fast growth of SWU requirements for high FRU share options. The study again finds an optimal solution in the form of 50%/50% share option for FRU and FR12.

FR deployment in the form of 100% FRU still poses spent fuel treatment issue despite causing a significant reduction in spent fuel accumulation when compared with the BAU case. Options for FR introduction with a FRU share up to 50% and a closed NFC show positive effects on SNF accumulation. SNF accumulations for FRU share options of 0%, 25% and 50% drop to zero level in 2065, 2080 and 2090, respectively. Similar results are obtained for Pu and MA inventories in long term storage facilities for LWR spent fuel.

Comparisons of the options show that those with FRU share lower than 50% give less FP and MA accumulations, since FRU gives the opportunity of implementing a solution wherein only fission products accumulated. A comparison of considered FR share options show that options with FRU share larger than 50% result in reducing the FP and MA accumulation in spent fuel present in long term storages, since FRU provide an prospective solution of reducing the radiotoxicity of accumulated spent fuel.

## XIX-2. ECONOMIC ASPECT OF FAST REACTOR DEPLOYMENT SCENARIOS, $^{235}U$ LOAD VERSUS U-PU LOAD

To assess transition scenarios of dynamic nuclear energy systems regarding sustainability, the GAINS project, following INPRO methodology, has used the electricity generation cost (or the levelized unit electricity cost – LUEC). NEST tool has been developed for calculation of LUEC. The main three components of LUEC are typically capital, operation and maintenance (O&M) and fuel costs. In this study we focus on the fuel cost, while recognising the capital and O&M costs as the significant part of total levelized cost. Fuel cycle cost analysis is based on a cost breakdown structure for a specific nuclear fuel cycle scheme, which includes fuel cycle components from uranium mining to waste HLW disposal.

Reference fuel cycle cost data are compiled in Table XIX-3 to perform comparison of synergistic and separate cases regarding levelized fuel cycle unit.

TABLE XIX-3 FUEL CYCLE REFERENCE SERVICE COST

| Fuel cycle facility | Unit | Service cost reference |
|---|---|---|
| Uranium | | 80-450 |
| Conversion | $/kgHM | 10 |
| Enrichment | $/SWU | 110 |
| Fuel UOX | $/kgHM | 275 |
| AFR storage | $/kgHM | 200 |
| Fuel fabrication MOX | | 1500 |
| Fuel fabrication metal | | 2000 |
| Reprocessing UOX | | 1300 |
| Reprocessing MOX | | 1500 |
| Reprocessing blanket | | 300 |
| Reprocessing metal fuel | | 2000 |
| LWR SNF direct disposal | $/kg(HM) | 800 |
| HLW direct disposal | $/kg(HM | 400 |

Figures XIX-18 and XIX-19 show levelized fuel cycle unit cost associated with different reactors. LUEC was calculated using the reference cost units for all fuel cycle steps for 80 $/kgU and 260 $/kgU, respectively. The options are represented by LWR operating in once-through fuel cycle, FR with BR=1 using own reprocessed Pu, FR using LWRs Pu for first loading and first 3 years of refuelling, FR12 with BR=1.2 using own reprocessed Pu, FR12 using LWRs Pu for first loading and first 3 years of refuelling, and the five variants of a heavy liquid metal cooled reactor (HLMR):

- HLMR using LWRs Pu for first loading
- HLMR using FR Pu for first loading
- HLMR using FR12 Pu for first loading
- HLMR using enriched U for first loading
- HLMR using own reprocessed fuel.

Fuel cycle component encompasses uranium cost, reprocessing, fuel reload, first fuel load, spent fuel (SF) disposal and high level waste (HLW) disposal.

Levelized fuel cycle cost of HLMR using enriched U (U=80 $/kgU) for first loading is in the range between HLMR using LWRs Pu for first loading and Pu from fast reactors. It is

comparable to levelized fuel cycle cost of LWR operating in once through fuel cycle. Levelized cost of HLMR with uranium start up is cheaper than then one of FR12.

So it is available technology economically achievable under existing uranium cost.

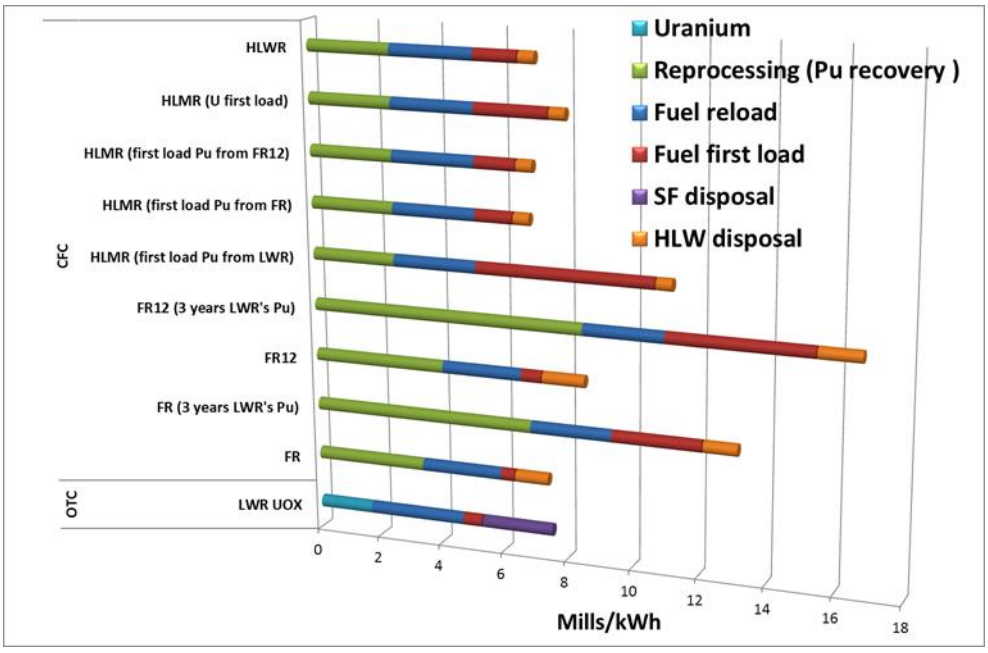


*FIG. XIX-18. Levelized fuel cycle cost, U= 80 $/kgU.*

If uranium cost increases up to 260 $/kg U, levelized fuel cycle cost of HLMR using enriched U becomes lower than the levelized fuel cycle cost of LWR operating in once-through fuel cycle. On the other hand, it approaches very closely the fuel cycle cost of HLMR using Pu from LWRs. The latter option becomes more economic as U cost increases. For the U cost 260 $/ kg U, the levelized cost of HLMR with uranium start-up is still lower compared to the one of FR12 using Pu from LWRs for the first loading and the first 3 years of refuelling. However, it becomes more expensive than for FR12 using Pu from LWRs for first loading. So, it can make economic sense to start from U first loading of HLMR with further replacement to first loading based on Pu from LWR/FR.

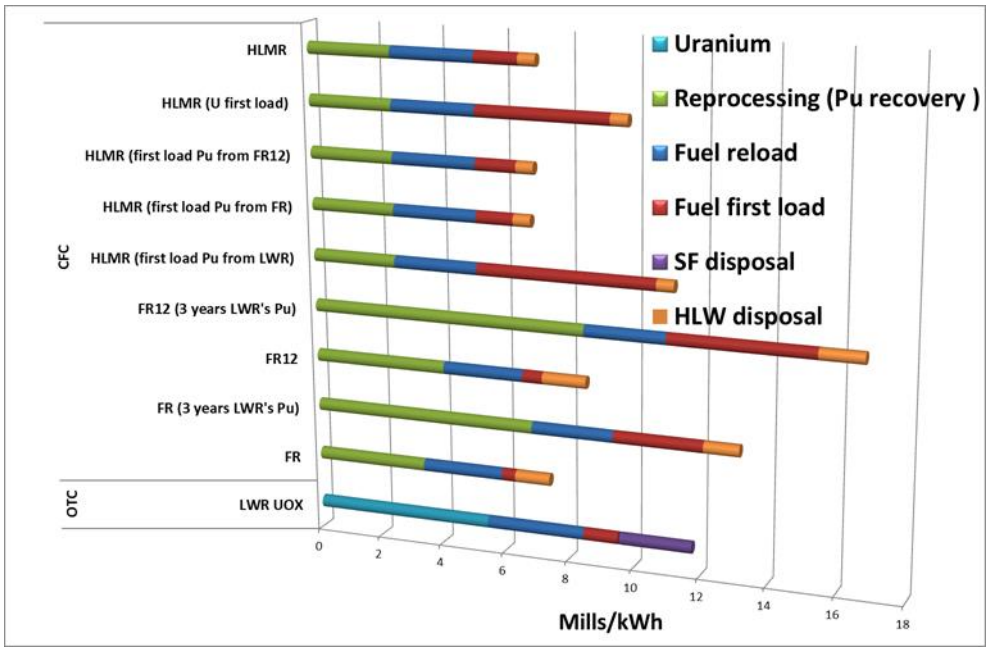


*FIG. XIX-19. Levelized fuel cycle cost, U=260 $/kgU.*

Some intermediate results of study were presented at HLMC – 2013 [XIX-9].

## REFERENCES TO ANNEX XIX


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