ANNEX XIV.

SENSITIVITY ANALYSIS OF SYNERGISTIC COLLABORATIVE SCENARIOS TOWARDS SUSTAINABLE NUCLEAR ENERGY SYSTEMS

XIV-1. BACKGROUND

The approach applied in the study is based on the internationally verified framework developed in the INPRO collaborative project "Global Architecture of Innovative Nuclear Energy Systems with Thermal and Fast Reactors and a Closed Fuel Cycle" (GAINS) GAINS project [XIV-1] includes 8 framework cases for Homogeneous and Heterogeneous (multi-group) world for high and moderate demand scenarios based on once-through and closed fuel cycle. The INPRO collaborative project SYNERGIES - Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability applies and amends the analytical framework developed in GAINS to model more specifically the various forms of collaboration among countries, assess benefits and issues relevant for collaboration and identify those collaborative scenarios and architectures that ensure a 'win-win' strategy to both, the suppliers and users.

The GAINS framework classifies non-personified countries into three country groups according to their nuclear fuel cycle strategies: NG1 countries pursue fast reactor programme and perform recycling of SNF; NG2 countries either directly dispose of the SNF or send it to NG1 for reprocessing; and NG3 countries are LWR based newcomer countries that send the SNF back to NG1 or NG2. The analysis methodology in this study is based on varying the allocation of future nuclear energy generation share of each country group as function of time for assessment of different scenarios, in comparison to the GAINS studies where the NG1:NG2:NG3 ratio was kept fixed at 40:40:20.

The sensitivity analysis is targetted on studying the behavior of global nuclear energy system shares in terms of its key parameters and stress limits under variations in country group. The GIANS studies were performed under fixed NG1:NG2:NG3 share ratio held at 40:40:20. This study explores possibility of transition of NG1 and NG2 groups under changes in NG1:NG2 proportion. The study also assesses impact of NG3 share variation on NG1/NG2 front end and back end fuel cycle requirements.The present study assumes high demand scenario established by the GAINS for nuclear power generation demand growth based on long term energy demand scenarios developed by the IAEA and IPCC. According to the adopted high demand scenario, the energy demand grows to 5000 GW(e).year in 2100 and flattens afterwards.

The base case BAU-FR is considered with three reactor types namely LWR, HWR and FR (BR=1.0). Brief description of reactor characteristics used in the study is provided in Table XIV-1. The fast reactors are assumed to replace LWRs gradually upon introduction. The share of HWRs in nuclear energy mix is assumed to be constant at 6% and independent of FR introduction.

TABLE XIV-1. GENERAL CHARACTERISTICS OF THERMAL AND FAST REACTORS

Parameter	LWR	HWR	FR (BR~1)		
Fuel Type	UOX	UOX	MOX-depleted U		
Electric capacity, MW(e)	1000	600	870		
Thermal efficiency, %	33	30	42		
Load factor, %	85	85	85		
Life time, year	60	60	60		
Core fuel burnup, MWday/kg	45	7	65.9		
Construction time, year	5	5	5		
Uranium enrichment, %	4	0.711	-		
Cooling time, year	5	5	2		
Reprocessing time, year	1	1	1		
			core	axial blanket (depleted U)	radial blanket (depleted U)
Fuel residence time, EFPD	1168	292	420	420	490
Mass of the core, tHM	78.7	83.4	12.6	5.5	6.2
Pu content in fresh fuel	-	-	0.22	-	-

Total FR power generation rate is constrained at 10 GW(e).year in 2030 and 400 GW(e).year in 2050 in accordance with the high case scenario of GAINS framework. Moreover, total plutonium inventory is kept close to zero in the storage. The FR introduction rate is not dictated by GAINS framework after 2050, but is limited by available plutonium in the spent fuel and overall growth rate of nuclear power generation.

Further assumptions used in the case study for nuclear energy system include: unlimited uranium resources; uranium enrichment tail assay at 0.3% level; temporary spent fuel storage for HWRs; and SNF reprocessing with no heavy metal isotopes loss.

The MESSAGE tool was used for NES modelling for evaluating different energy development strategies under tailored constraints. The MESSAGE is an advanced nuclear energy system modelling code developed at the IAEA which performs energy balances with minimal discounting costs and provides an optimized forecast of the energy evolution with required level of detail.

XIV-2. MODIFICATION OF SOME GAINS FRAMEWORK ASSUMPTIONS

The modification of GAINS framework assumptions for non-synergistic nominal case was done and implemented in MESSAGE model [XIV-2, XIV-3], including industrial constraint on separation capacity, using U recovered from LWR and FR spent nuclear fuel and tracing flows for MOX fuel and Blanket fuel.

XIV-2.1. Industrial constraint on separation capacity

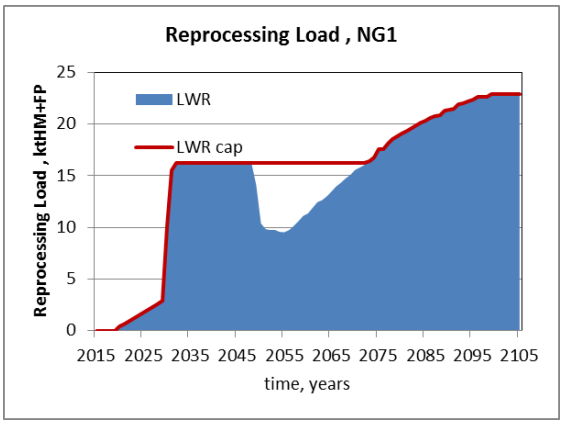

FIG. XIV-1. Reprocessing load in NG1 (reprocessing by requirement).

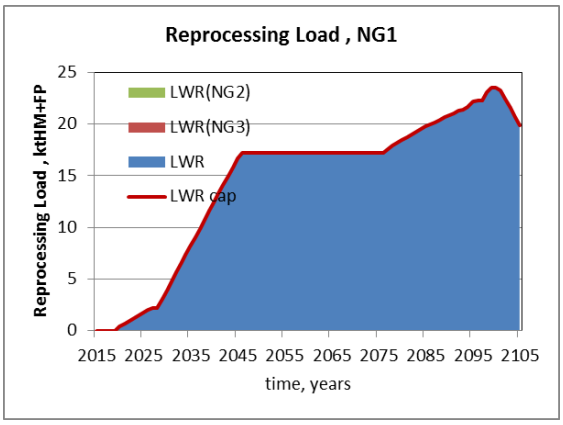

FIG. XIV-2 Reprocessing load in NG1 (industrial adjusted reprocessing).

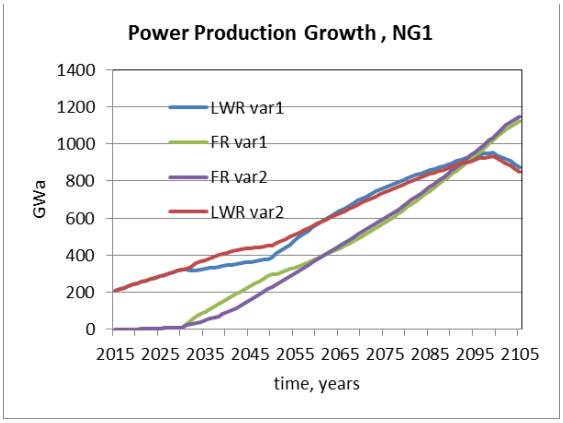

FIG. XIV-3. Power production growth in NG1.

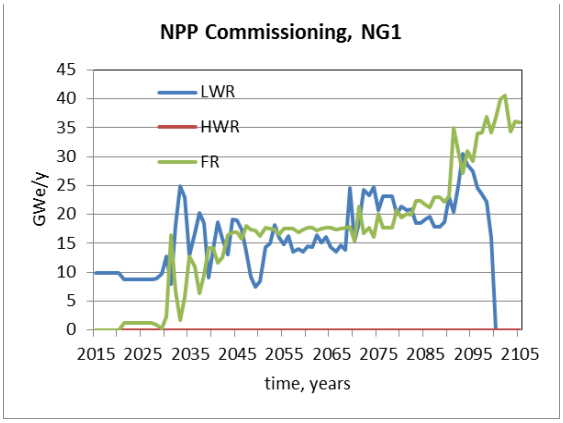

FIG. XIV-4. NPPs commissioning in NG1.

The scenarios studied in GAINS have been calculated by assuming that there is no limitation on fuel cycle facility capacities. According to this assumption, for example, the reprocessing depends on Pu demand without limitation except for the spent fuel availability. The GAINS objective was to provide just the amount of reprocessing capacity sufficient to support the specified FRs during the specified introduction period.

However, as GAINS pointed out, using unlimited separation results in high reprocessing requirements for a very short period while the stored inventory built up since 1970 is reprocessed, followed by a much lower level based only on the current rate of discharge and cooling. It is unrealistic to build expensive reprocessing facilities and only use them for a few years.

Figure XIV-1 shows the result for LWR reprocessing load (separation) for non – synergistic case. There are two issues attributed to reprocessing load: first, the introduction of a lot of reprocessing capacities (up to 10 ktHM) in a few years (~ 1-3 years); second, reprocessing facilities do not operate on full capacities during their life time because of a shortage of spent fuel occurs after some year of operation. One of the possible ways to avoid this problem was recommended in GAINS and is to base on industrial reprocessing approach. In this case, the reprocessing capacity is limited by the user. Based on this recommendation we modified GAINS approach to develop a more practical and, potentially, more realistic introduction and operation of reprocessing capacities. The introduction of new LWR

reprocessing capacity was limited to up to 0.850 ktHM/year spent fuel (counting only the heavy metal and fission products) till 2050, which corresponds to the capacity of the UP2 800 or UP3 plants at La Hague, and up to 3.0 ktHM/year spent fuel after 2050, respectively. Also, no capacity is removed until the unit has operated for a full life (40 years). The result is shown in Fig. XIV-2.

Modification of reprocessing capacities leads to the changing of the FR commissioning rate. They oscillate after 2030 versus stable introduction for GAINS variant. The FR share is slightly less than in GAINS case in medium term; nevertheless, the total FR demand is close to GAINS case after 2055.

XIV-2.2. U reprocessing and recycling in LWRs and FRs

In the study it was assumed for the framework base cases that the reprocessed uranium from thermal and fast reactor will be accumulated in stocks without recycling. It will be reasonable to use reprocessed FR uranium in FRs and reprocessed LWR uranium in LWRs as shown by red arrows in Fig. XIV-5. Another possible solution is to use reprocessed LWR uranium in HWR of NG2. We modified NG1 fuel cycle system as shown in the diagram from Fig. XIV-5. Figure XIV-6 shows reprocessed products stock with growing reprocessed uranium.

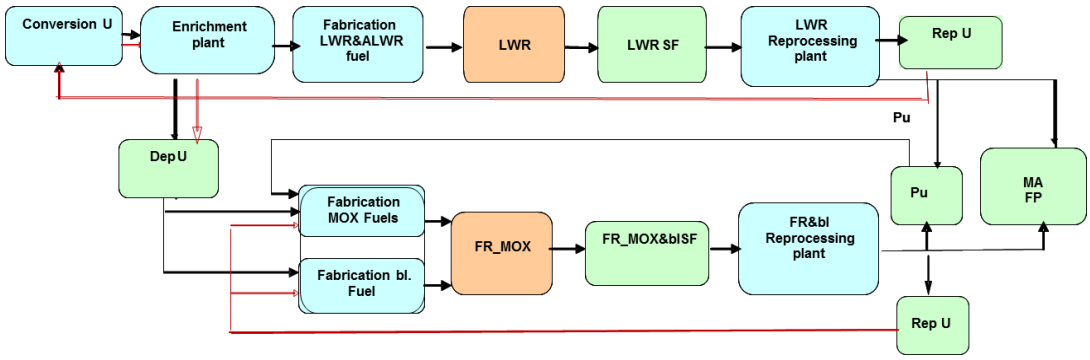

FIG. XIV-5. NG1 fuel cycle system of BAU with FR (BR~1.0) scenario.

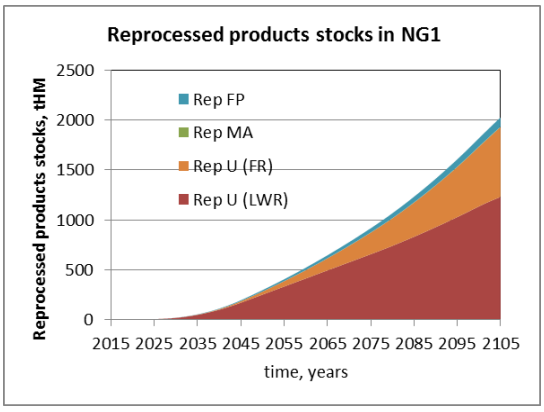

FIG. XIV-6. Reprocessed products stocks in NG1 without U recycling.

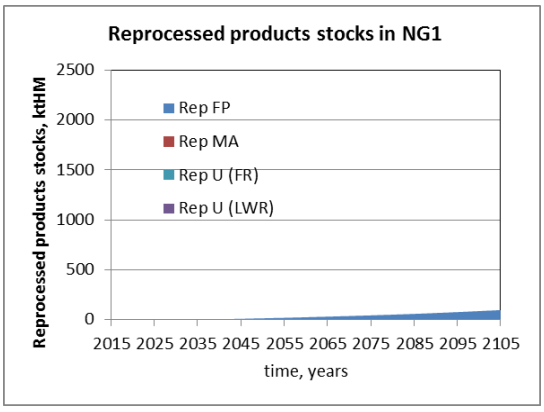

FIG. XIV-7. Reprocessed products stocks in NG1 with U recycling.

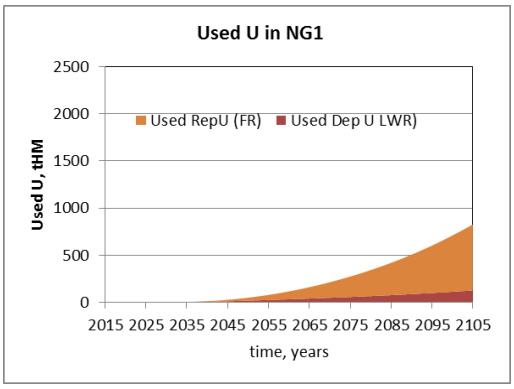

FIG. XIV-8 Using of reprocessed uranium in NG1.

The result is the accumulation of only MA and FP in reprocessed product stocks (Fig. XIV-7). All reprocessed uranium from FR consumes by FR without its accumulation in the stock. Reprocessed LWR uranium goes to re-conversion and re-enrichment and then is used for fuel fabrication. Using of repro uranium saves the natural uranium and removes reprocessed uranium from the stock. Nevertheless, the issue with separated U from thermal reactors doesn't fully resolve. Reprocessed uranium from stocks passes through re-enrichment processing into depleted uranium. FR can partly consume this uranium in addition to reprocessed uranium from FR, but insignificantly (Fig. XIV-8). So, most of the reprocessed uranium moves after enrichment processing to the depleted uranium stock, as depleted uranium.

XIV-2.3. Tracing of MOX and Blanket fuel flows

Table XIV-1 presented the major specifications of the break-even FR. Reactor parameters of the FR were homogenized to a one-region core like LWRs or HWRs in GAINS study to make the input for fuel cycle calculation codes more convenient to calculate. SYNERGIES project pays special attention to fuel cycle facilities and possible way of their sharing. The fabrication of MOX fuel and fabrication of blanket fuel is better to consider separately, providing valuable analysis of nuclear fuel cycle. Cost of MOX fuel fabrication and blanket fuel fabrication is essentially different. Fabrication of these fuels is also technologically different. We separated the flows for MOX fuel and Blanket fuel as shown in Fig. XIV-5. The result is presented in Fig. XIV-10.

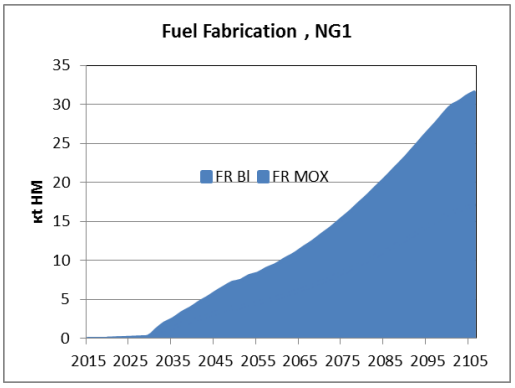

FIG. XIV-9. FR fuel fabrication, high heterogeneous synergistic case, non-separated flows.

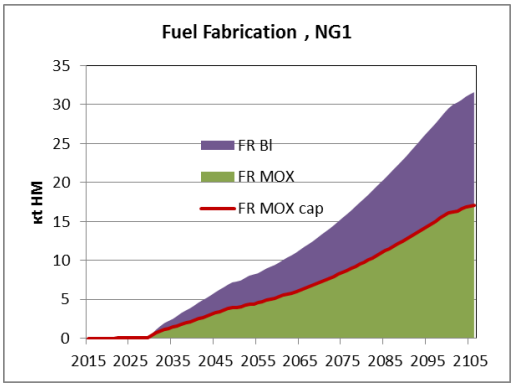

FIG. XIV-10. FR fuel fabrication, high heterogeneous synergistic case, separated flows.

XIV-3. SENSITIVITY ANALYSES OF WORLD HETEROGENEOUS SCENARIOS WITH DIFFERENT NG3 SHARES

The modified GAINS non-synergistic nominal case was used as a starting point for sensitivity analysis. Variation in market share of NG3 is examined in the sensitivity analysis by changing the assigned share of world nuclear power growth to NGs. The world power growth is assumed to follow the GAINS high case, reaching 1500 and 5000 GW(e).year marks in 2050 and 2100, respectively and flattening after the end of current century. NG1 share is kept fixed at nominal fraction of 40% and NG3 share is varied in intervals of 10, 20, 30, 40 and 50% (remaining being NG2) in 2100. The assessment of NG3 share variation is carried out for NG1/NG3 fuel cycle front end and back end requirements.

XIV-3.1. Power production growth in NGs

The power production growth in NG1 and NG3 under different NG3 market shares is shown in Fig. XIV-11 and Fig. XIV-12. In the analysis, total demand curve follows GAINS high demand case with 5000 GW(e).year in 2100. Therefore, increase in NG3 share is a result of reduction in NG2 share.

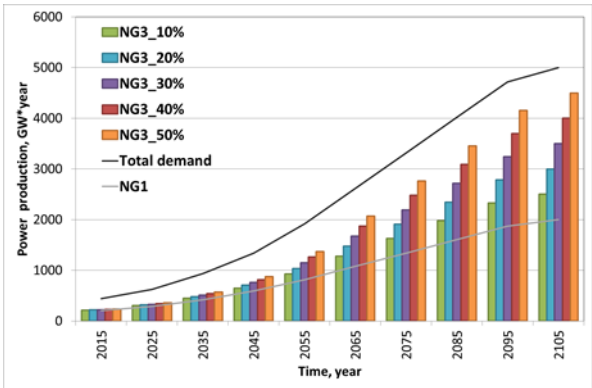

FIG. XIV-11. Power production growth in NG1,NG3

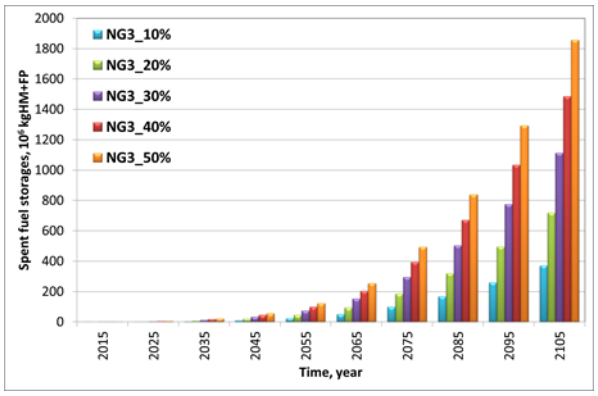

FIG. XIV-12. Power production growth in NG3

XIV-3.2. NG3 results for NFC requirements for non-synergistic and synergistic cases

Heterogeneous non-synergistic case does not consider nuclear material cooperation and transfer between the NG groups. It is assumed that all NGs possess equal access to naturally occurring uranium all NGs contain their own front end and back end requirements of fuel cycle. In this case, assessment was carried out for fuel cycle requirements of NG3 and impact of synergistic cooperation between NG1 and NG3.

Figures XIV-13 and XIV-14 show cumulative natural uranium consumption and SWU requirement in NG3. Increase in SWU requirements is observed to about 10 million SWU/year by 2050 in the medium term and up to about 70 million SWU/year by 2100 for 10% NG3 share. The SWU requirements increase significantly for 50% NG3 share reaching 50 million SWU/year by 2050 and 350 million SWU/year by the end of the century. For comparative studies, currently available world SWU capacity is about 50 million SWU/year which is reached by 50% NG3 share scenario in the medium term.

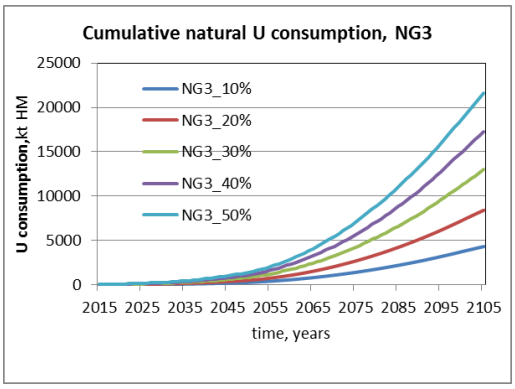

FIG. XIV-13. Cumulative natural uranium consumption in NG3.

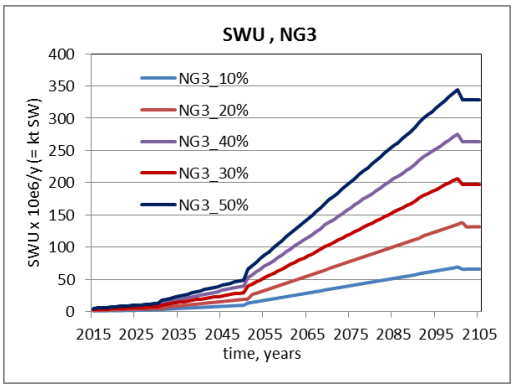

FIG. XIV-14 SWU requirements in NG3.

SNF accumulation in NG3 long term storage facilities is shown in Fig. XIV-15. The SNF long term storage in NG3 rises to 17 ktHM by 2050 and 300 ktHM by 2100 for NG3 shares of 10% and more severely it increases to 85 ktHM in 2050 and 1500 ktHM by 2100 for 50% NG3 share. Current global SNF accumulation in storage facilities stands at about 250 ktHM [XIV-4, XIV-5].

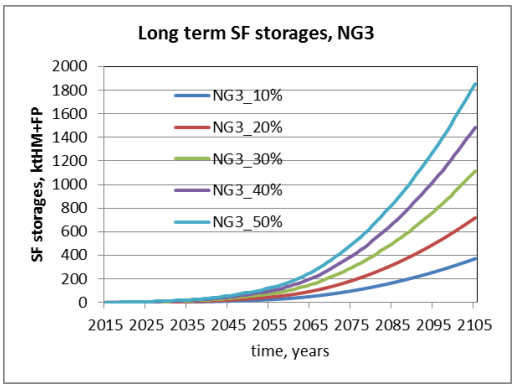

FIG. XIV-15. Long term SF storage in NG3.

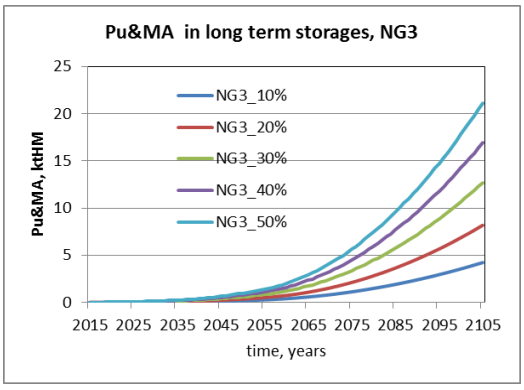

FIG. XIV-16. Pu & MA in NG3 long term storages.

Accumulation of Pu and MA in long term storages is shown in Fig. XIV-16. This value is varied in the range 0.2- 1 ktHM on medium term by the year 2050 and 3.5-18 ktHM on long term by the year 2100.

Nuclear material exchange between NGs is permitted for the synergistic case, which facilitates the NG countries to follow their preferred nuclear fuel cycle strategies. NG3 group is assumed to follow strategy of deploying LWRs with limited fuel cycle structure and relies on NG1 for fuel cycle services, including front-end services of mining, converting and enriching uranium and fabricating fresh LWR fuel, and back-end services of taking back used LWR fuel after it has cooled. In the synergistic case, NG3 countries can benefit by avoiding development and construction of own nuclear fuel cycle facilities or handling large inventories of dry spent fuel. The synergistic case does not require dry storage facility at NG3 and SNF will be only placed in cooling pools of NG3 for initial cooling.

Handling and shipment of fresh and spent nuclear fuel among NG groups will be a concern in the synergistic scenario. The amount of fresh fuel and spent fuel transported between groups is shown in Fig. XIV-17 for all considered NG3 shares. Fuels transported between regions are in the range of 2-12 ktHM/year in the middle term and rise up to 10-65 ktHM/year in long term by the end of the century.

The fresh fuel shipped to NG3 reaches level of 5-20% in short, 14-45% in medium and 40-95% in long term, respectively, of combined NG1-NG3 fresh fuel requirement.

Transported nuclear materials are assumed to be handled as Category-III, with fresh fuel having only LEU and spent fuel sealed in radiation barrier as described by the GAINS framework.

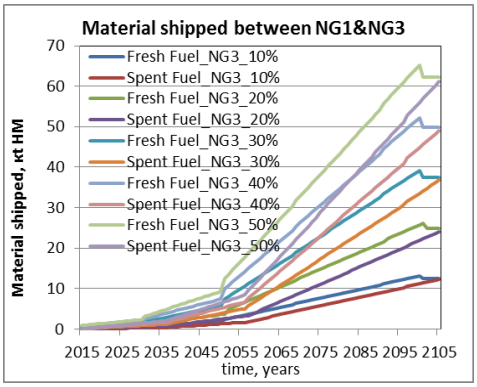

FIG. XIV-17 Material shipped between NG1&NG3.

XIV-3.3. Impact of NG3 share on NG1 nuclear fuel cycle

In the synergistic case, increase in NG3 share will lead to increased availability of material for fast reactors of NG1 since NG1 is responsible for providing all fresh fuel to NG3 and taking back entire spent fuel of NG3. Power production growth curves of LWRs and FRs in NG1 for the synergistic case are shown in Fig. XIV-18 and Fig. XIV-19, respectively. Significant impact of NG3 share on power production structure of NG1 is observed in the medium and long terms. The FR power production growth in NG1 becomes significant after 2050 and reaches 1300-1900 GW(e).year level in 2100 for NG3 share of 10-50%. The power production growth of LWRs in NG1 increases to a level above 900 GW(e).year for the non-synergistic case but reduces to almost zero in the synergistic case by 2100 in the synergistic case with 50% share of NG3. There is no impact of change in NG3 share on NG1 power structure in short term, which will be explained in subsequent section.

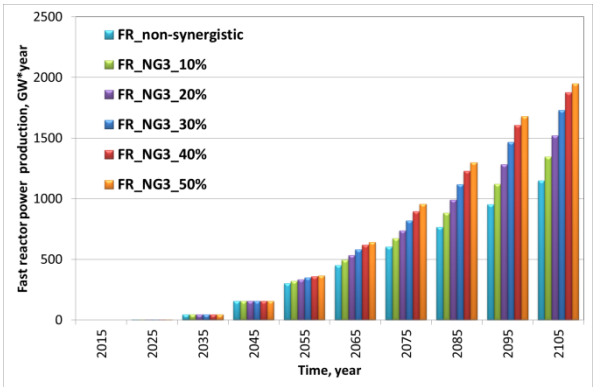

FIG. XIV-18. FR Power Production Growth in NG1.

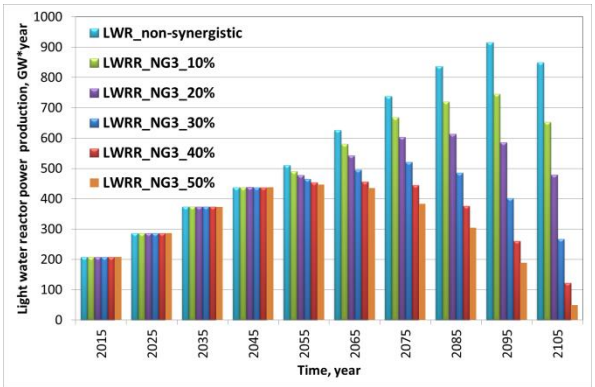

FIG. XIV-19. LWR Power Production Growth in NG1.

The increase in NG3 share although decreases the LWR growth, but LWR front end and back end fuel cycle capacities of NG1 will increase due to fuel cycle service requirements of NG3 in synergistic case in all terms. Moreover, the cumulative depleted uranium will also

increase in NG1. The FR power production increases FR-MOX fuel fabrication capacity with increased NG3 share in medium and long terms. Therefore, NG1 must consider upgradation of front end fuel cycle infrastructure in short, medium and long terms whereas upgradation of its back end infrastructure in medium and long terms for synergistic cooperation with NG3. Large fuel cycle facilities development and retailing of fuel cycle services would benefit NG1 in the collaboration.

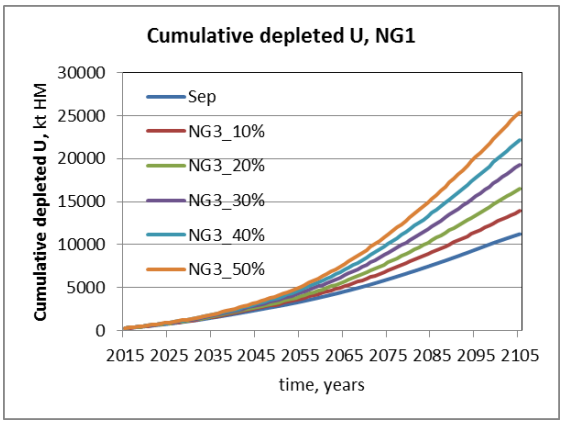

FIG. XIV-20. Cumulative depleted U inNG1.

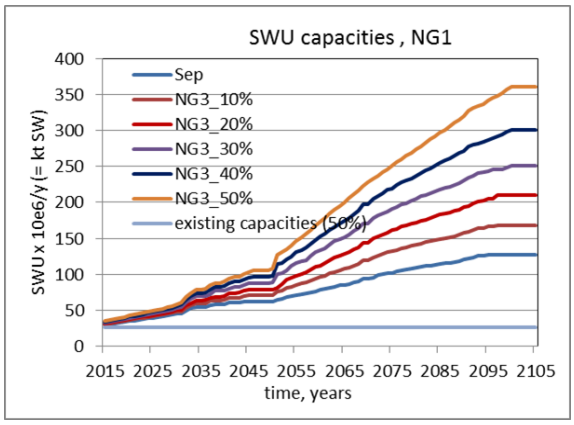

FIG. XIV-21. SWU capacities in NG1.

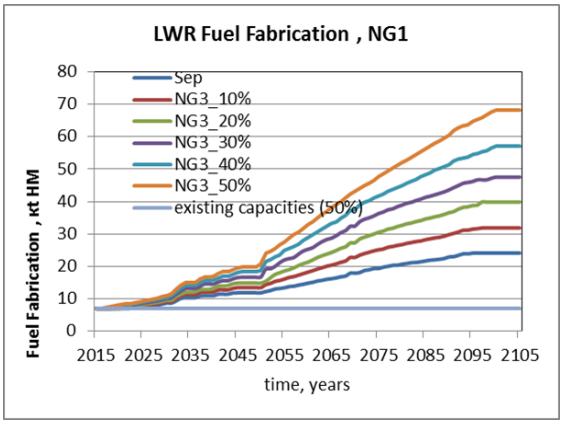

FIG. XIV-22. LWR Fuel Fabrication in NG1.

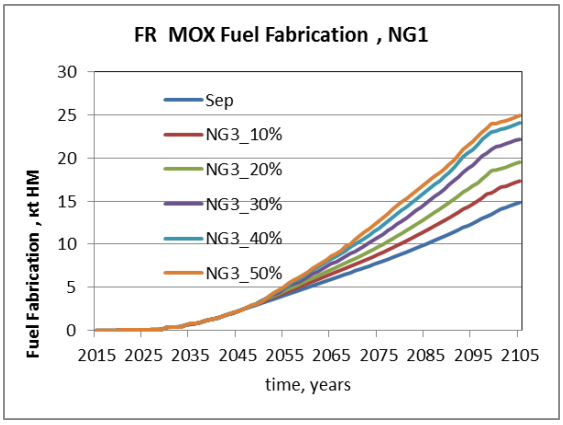

FIG. XIV-23. FR MOX Fuel Fabrication in NG.

It is considered that reprocessing facilities operate at full capacity over complete lifetime and introduction of new LWR reprocessing capacities is limited to 850 t/year of SNF until 2050 and to a value of 3000 t/year of SNF afterwards. Since the LWR fuel reprocessing capacity is limited at 850 t/year, all NG3 shares must consider same reprocessing load until 2050. As a result recovered plutonium is same for all values of NG3 share from 10% to 50% and same number of FRs is introduced, discharging same amount of SNF for reprocessing as shown in Fig. XIV-24 and Fig. XIV-25. LWR reprocessing capacity in NG1 is increased to a maximum of 3000 t/year after 2050 due to increased LWR SNF supply from NG3. The LWR reprocessing capacity becomes 20-32 kt/year in the medium term for 10-50% share of NG3 countries.

There is no limit set on reprocessing capacity of FR spent fuel, with assumption that it remains same till 2050 for the short term. The FR reprocessing capacity increases to 28-41 kt/year for 10-50% NG3 share by 2100.

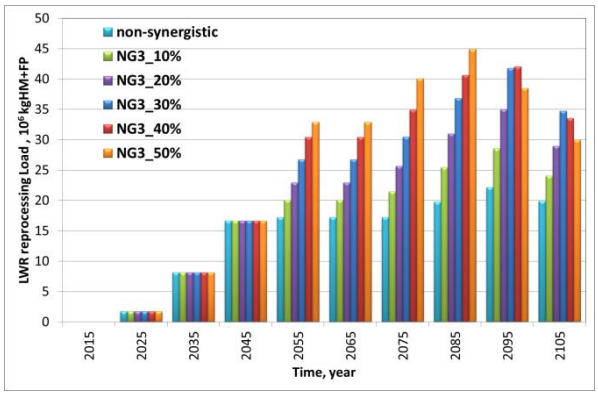

FIG. XIV-24. LWR Reprocessing Capacities in NG1.

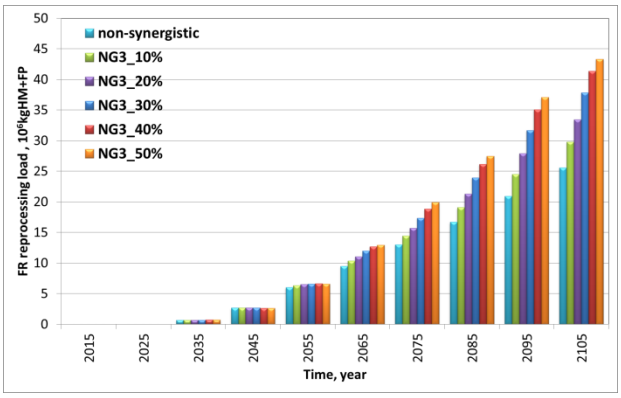

FIG. XIV-25. FR Reprocessing Capacities in NG1.

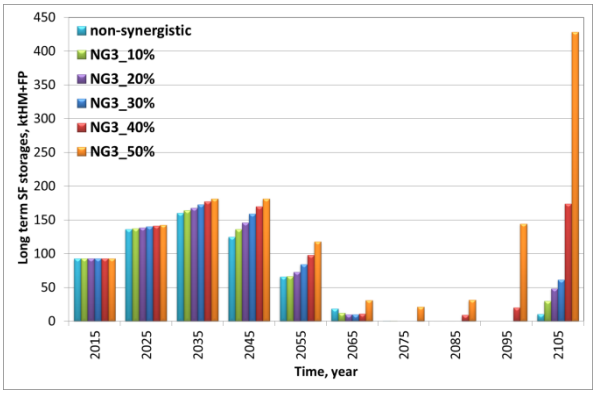

FIG. XIV-26. LWR Long term SF storages in NG1.

The long term SNF storage requirements at NG1 shown in Fig. XIV-26 constitute SNF from both NG1 and NG3 for the synergistic case. The SNF inventory vanishes in around 2075 for 10-40% share of NG3, but starts to accumulate again since the reactors commissioned after 2030 start to decommission and new FRs installation is limited by total nuclear demand growth. Full core discharge of decommissioned reactors can be reprocessed to supply additional plutonium for loading in new FRs.

Available spent fuel inventory is not completely used up for NG3 share at 50%. It decreases to 20 kt in the medium term but increases back due to limitation on installation of new FRs by overall demand growth capacity in NG1. Nevertheless, the long term storage requirements of spent fuel are considerably reduced in the synergistic cooperation approach.

FR spent fuel is not accumulated in the long term storage since it is moved to reprocessing soon after cooling.

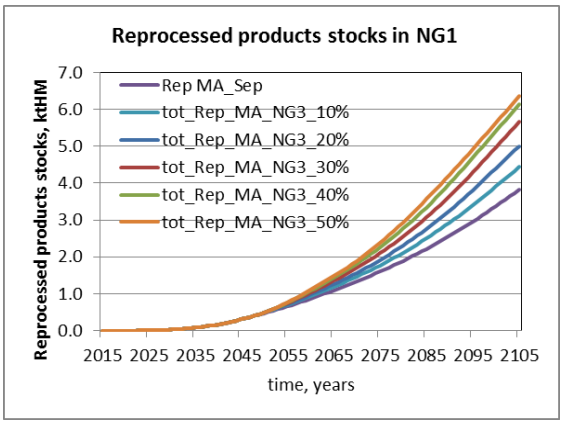

FIG. XIV-27. Reprocessed MA stocks in NG1.

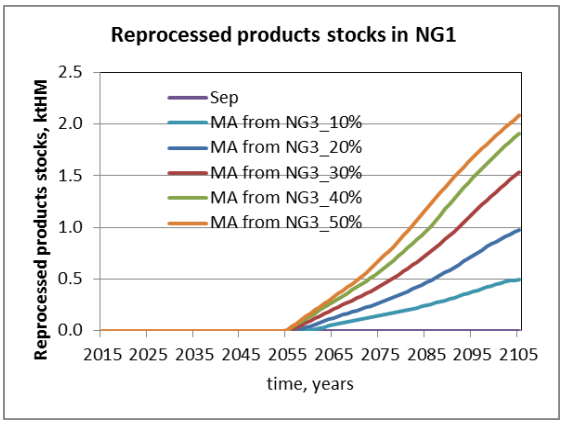

FIG. XIV-28. Reprocessed MA stocks from NG3 in NG1.

Figures XIV-27 and XIV-28 show accumulation of MA&FP total amount in NG1 for all NG3 shares. In this scenario, MA and FP generated by reprocessing of NG3 spent fuel is kept in NG1. Figures XIV-29 and XIV-30 show accumulation of MA&FP total amount generated by reprocessing of NG3 spent fuel in NG1. Reprocessed MA stocks from NG3 in NG1 increase as 0.45, 0.86, 1.34, 1.7 and 1.89 ktHM, respectively, and reach 11%, 20%, 27%, 31% and 33%, respectively, of total MA accumulation on long term by the end of century in NG1. MA from NG3 spent fuel can be returned to NG3 for disposal. The utilization of MA in reactor or a transmutation system can be a sustainable solution for this problem. The amount of separated FP increases with NG3 share from 80 ktHM for separate case up to 140 ktHM for 50% NG3 share.

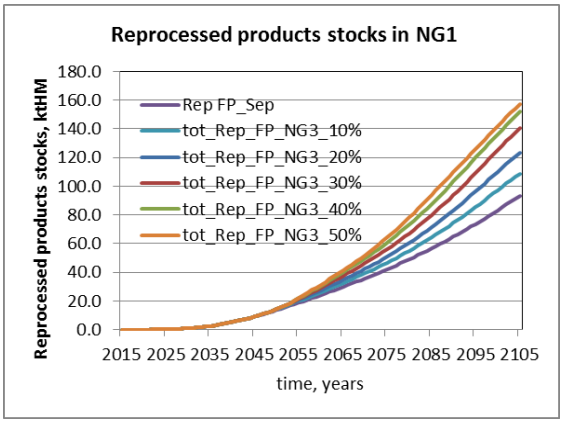

FIG. XIV-29. Reprocessed FP stocks in NG1.

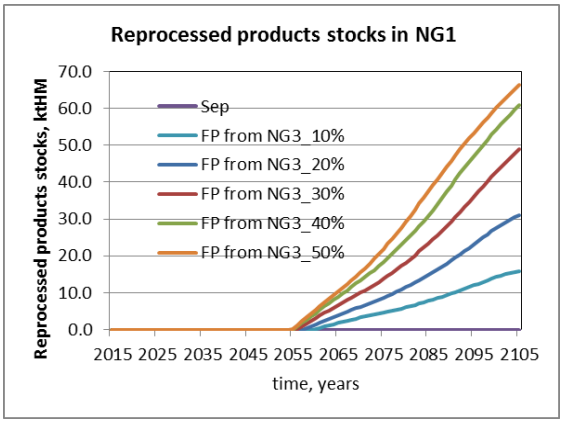

FIG. XIV-30. Reprocessed FP stocks from NG3 in NG1.

XIV-3.4. Impact of NG3 and NG2 on NG1 (nominal case)

The previous cases did not consider nuclear material transfer between NG1 and NG2. NG2 countries follow the NFC strategy to either dispose of spent fuel or send it abroad for recycling. Synergistic cooperation between NG1 and NG2 can provide a solution to the global SNF accumulation problem and associated waste disposal issues.

In this study, nominal case is analyzed for the scenario in which all SNF reprocessing of NG2 and NG3 takes place at NG1 along with its own spent fuel.

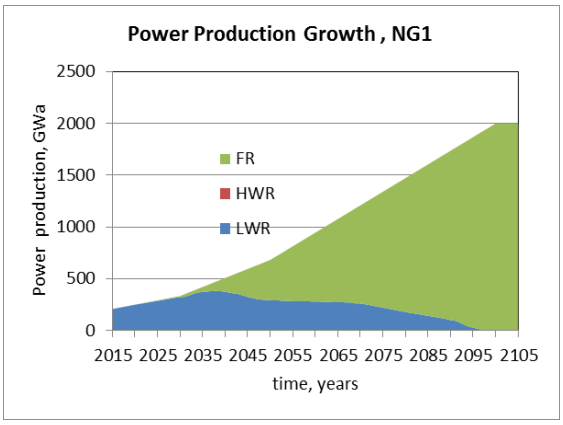

FIG. XIV-31. Power production growth in NG1,Synergy with NG3&NG2

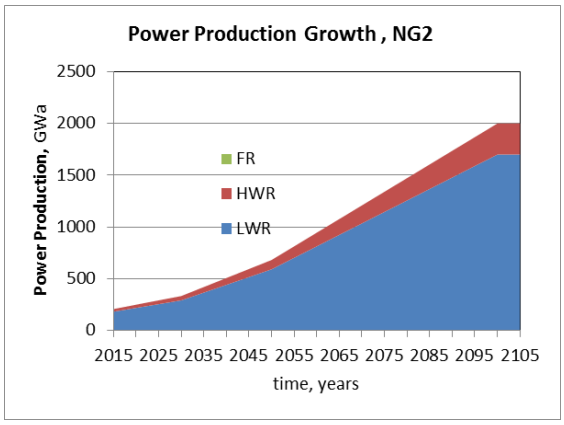

FIG. XIV-32. Power production growth in NG2

Figures XIV-31 and XIV-32 show the power production growth and reactor mix share in NG1 and NG2. The power demand share of each group is 40% of total world demand in 2100. FR's power reaches 100% around 2095. The HWRs is at 6% of the total generation, independent of the FR introductions. NG3's power share increases linearly from 0% in 2008 to 20% in 2100.

Fig. XIV-33 shows that all LWRs in NG1 are replaced by FRs after 2040. The FR power production is also increased due to added supply of plutonium from NG2 SNF, being 30% more when compared to using SNF from NG3 only. This leads to significant impact of NG2 on NG1 nuclear power structure, with FRs introduction in NG1 increasing by 63% in medium term and by 38% in long term when compared with NG1-NG3 synergy scenario.

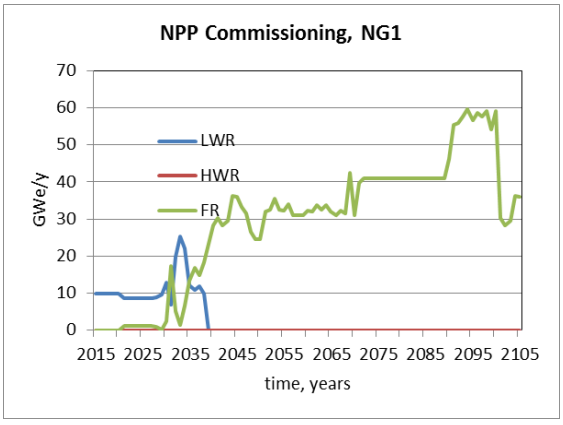

FIG. XIV-33. NPP commissioning in NG1.

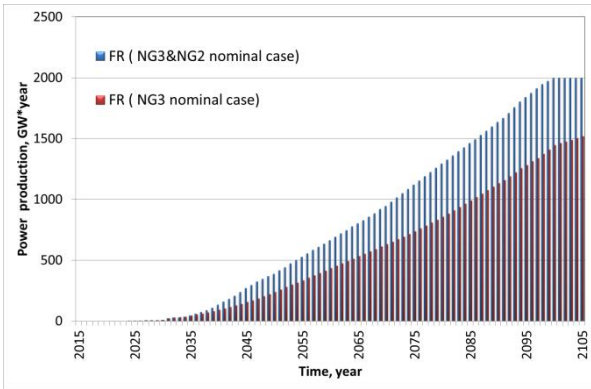

FIG. XIV-34. Comparison of FR power production growth (NG3&NG2 and NG3 impact).

Reprocessing load is shown in Fig. XIV-35 and Fig. XIV-36 for scenario of shipping NG2 and NG3 SNF to NG1 and scenario of returning only NG3 SNF to NG1, respectively for comparison among these cases. There is significant difference in both scale of reprocessing and structure of reprocessing in medium and long terms for both cases. The NG2 SNF reprocessing is limited due to constraint on reprocessing capacity set at maximum value of 850 t/year till 2050 and 3000 t/year of SNF afterwards. The limit on maximum capacity of reprocessing was increased to 3000 t/year after 2035 for the case of NG2 SNF transportation to NG1 as compared to the 2050 t/year limit in the NG3 SNF return case. The reprocessing

load at NG1 increases to 33 t/year initially but starts declining after 2045 to almost zero by 2100 for the NG1-NG2-NG3 synergistic case.

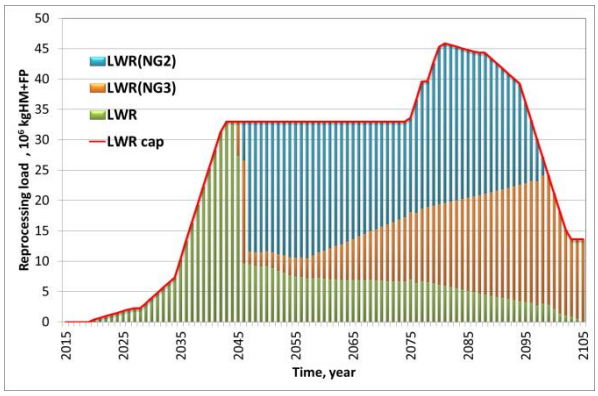

FIG. XIV-35. LWR Reprocessing load (NG3&NG2 impact)

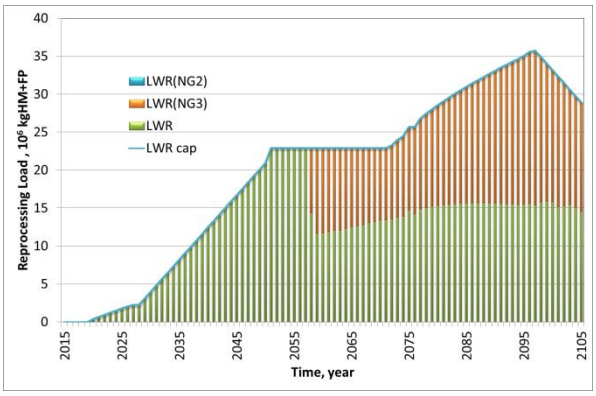

FIG. XIV-36. LWR Reprocessing load (NG3 impact)

The reprocessing load of FR fuel is also affected by the NG2 SNF as shown in Fig. XIV-37. The separation and reprocessing requirements of FR fuel increase on introduction of more FRs as more SNF is available from NG2 countries. Thus significant impact of NG2 SNF is observed on both LWR and FR fuel reprocessing capacities.

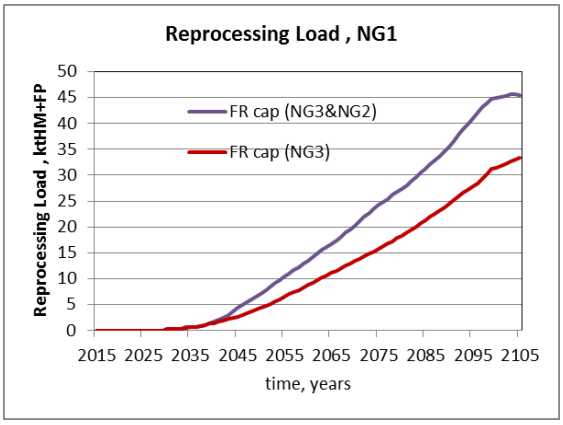

FIG. XIV-37. FR Reprocessing load (NG2 impact).

NG2 has historically accumulated SF representing a half of world accumulation (~ 100 ktHM).

Figures XIV-38 and XIV-39 give the continuous growth of stored SF (ready for disposal or reprocessing). It should be noted that although the HWR power production is less than the one from LWR, the accumulation of HWR spent fuel is even slightly more than for LWR spent fuel case. Only LWR SNF is sent for reprocessing in the case under consideration, spent fuel from HWRs being temporarily stored in NG2.

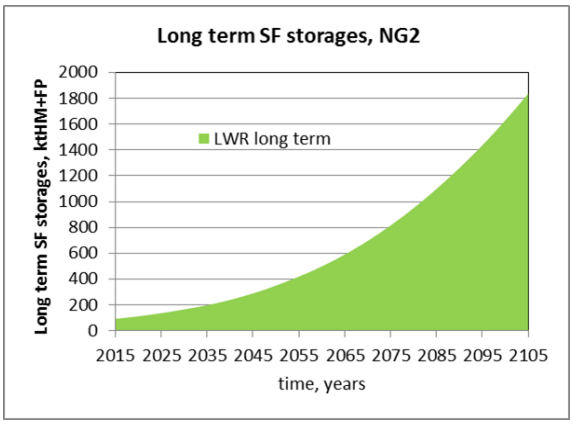

FIG. XIV-38. LWR Long term storage in NG2.

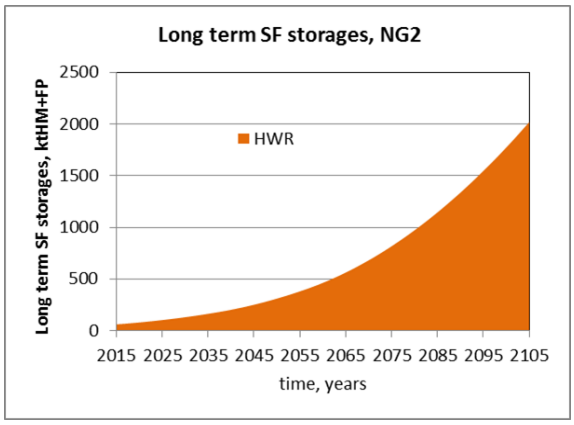

FIG. XIV-39. HWR Long term storage in NG2.

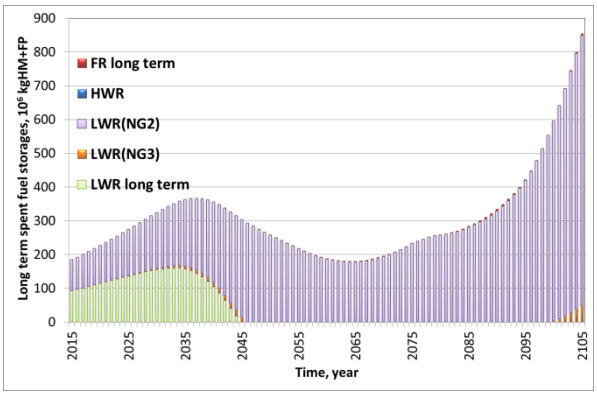

FIG. XIV-40. LWR Long term storage in NG1(NG3&NG2 impact).

Long term storage requirement of LWR SNF in NG1 is provided in Fig. XIV-40, which shows that NG2 SNF could not be completely utilized. The NG2 SNF inventory first reduces to 200 t by 2065 but increases afterwards due to increased LWR SNF requirement by NG1 for constructing maximum FRs. Further introduction of FRs is limited by total power demand limit of 2000 GW(e) in year 2100 in NG1.

Reprocessing rate and nuclear power demand of NG1 play an important role in FR introduction rate and NG1 reprocessing capability of SNF from other NGs. Under the aforementioned cases, a part of SNF from NG2 and/or NG3 has to be stored or disposed of. SNF accumulation would further worsen on increasing the breeding ratio of FRs. One of the approaches to alleviate this issue is to introduce new FRs in NG2 and/or NG3 without associated fuel cycle.

It is a matter of interest to calculate NG1 power demand that completely resolves global SNF accumulation problem. High growth scenario in NG1 was assumed for this purpose. Furthermore, NG1 high demand growth was considered to assess the SNF consumption capability of NG1 for spent fuel coming from all NGs.

XIV-3.5. Impact of NG3 and NG2 on NG1 (High NG1 Growth, from 50% to 65%, case)

The high NG1 demand growth from 50% to 65% of world demand (3250 GWyear in 2100) is presented in Fig. XIV-41. The NG3 power demand is kept at nominal level of 1000 GWyear in 2100. As far as the global demand is 5000 GWyear in 2100, the NG2 power demand is less than in nominal case and archives only 750 GWyear in 2100.

The FR power production increases from 2000 to 2500 GWyear in 2100 in comparison with the nominal demand growth (Fig. XIV-42) as all SF from NG2&NG3 are available for reprocessing and the total demand in NG1 is higher.

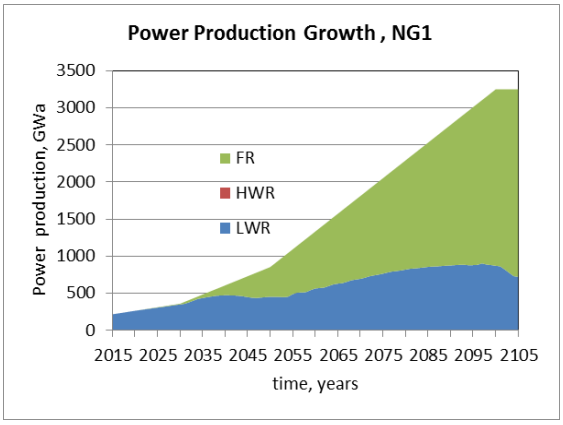

FIG. XIV-41. Power production growth in NG1, (High NG1 Growth case, Synergy with NG3&NG2).

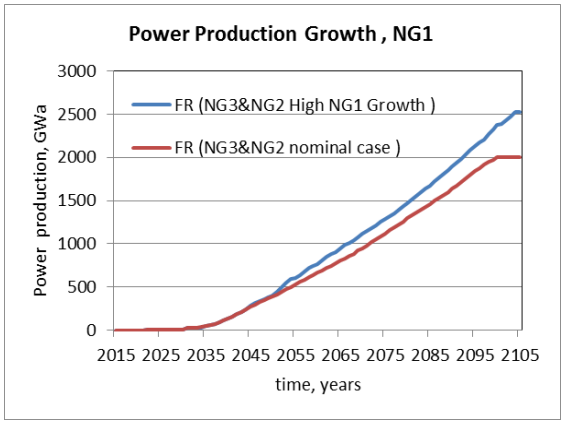

FIG. XIV-42. Comparison of FR power production growth (nominal and High NG1 Growth cases).

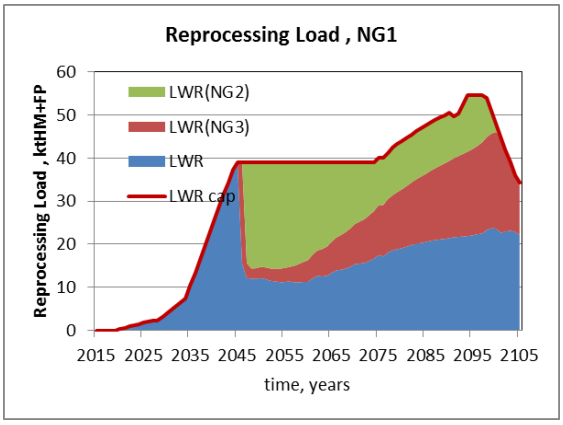

FIG. XIV-43. LWR Reprocessing load in NG1 (High NG1 Growth case, (NG3&NG2 impact).

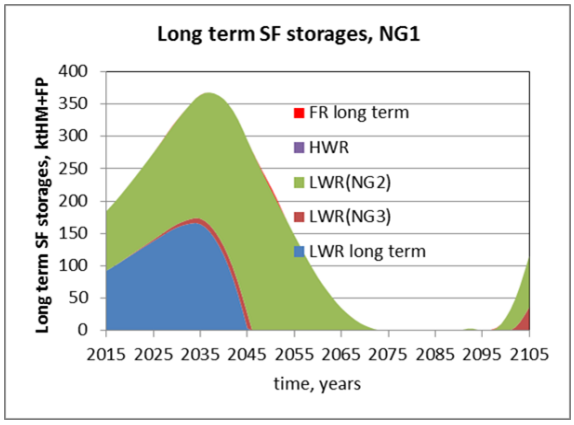

FIG. XIV-44. LWR Long term SF storages in NG1 (High NG1 Growth case, (NG3&NG2 impact).

Reprocessing capacities reach up 40 ktHM for the flat part of the reprocessing load (Fig. XIV-43), in comparison with 33 ktHM for nominal case (Fig. XIV-35), to support more FRs introduction in NG1. This scenario completely consumes SNF from all NG sources by year 2070 as shown in Fig. XIV-44. Hence in this case, SNF from NG2 and NG3, a waste in these groups, can act as a resource for NG1 for global transition to large scale nuclear energy deployment without SNF accumulation issues.

XIV-3.6. Natural U cost perspective

The uranium resources for this study data were taken from Red Book [XIV-6] and divided in five grades: “a”, “b”, “c”, “d”, “e”, f”, “g” according to their cost. Grades “a” - “e” refer to identified and undiscovered resources of various costs comprising 17.5 million tons of natural uranium, as it is shown in Table XIV-2. Grade “f” is associated with uranium in phosphates and has a deposit of 21600 kt of uranium with recovery cost in the range > 400 $/kgU. Natural uranium resources are limited by 39 million tons for the sum of all those

grades. Resource of grade “g” is associated with uranium in sea water. One supposes that grade “g” has practically unlimited resource with the cost of recovery higher than 450 $/kgU.

TABLE XIV-2. U RESOURCES

Recovery USD$/kgU	Identified Resources		Undiscovered Resources		Phosphates
	Reasonably Assured Resources	Inferred Resources	Prognosticated Resources	Speculative Resources	21 600 000 (f)
< 40 (a)	493900	187000			
40-80 (b)	1520900	876700	1624100		
80-130 (c)	1440700	808000	1073900	3543800	
130-260 (d)	923200	846200	143300	318300	
Cost range unassigned (e)				3733200	
Total	7096600		10436600		
	17533200				
	39133200				

Based on above presented uranium data natural cost, perspective for given high global demand was estimated. Results for different fuel cycle and collaboration strategies are presented in Fig. XIV-45.

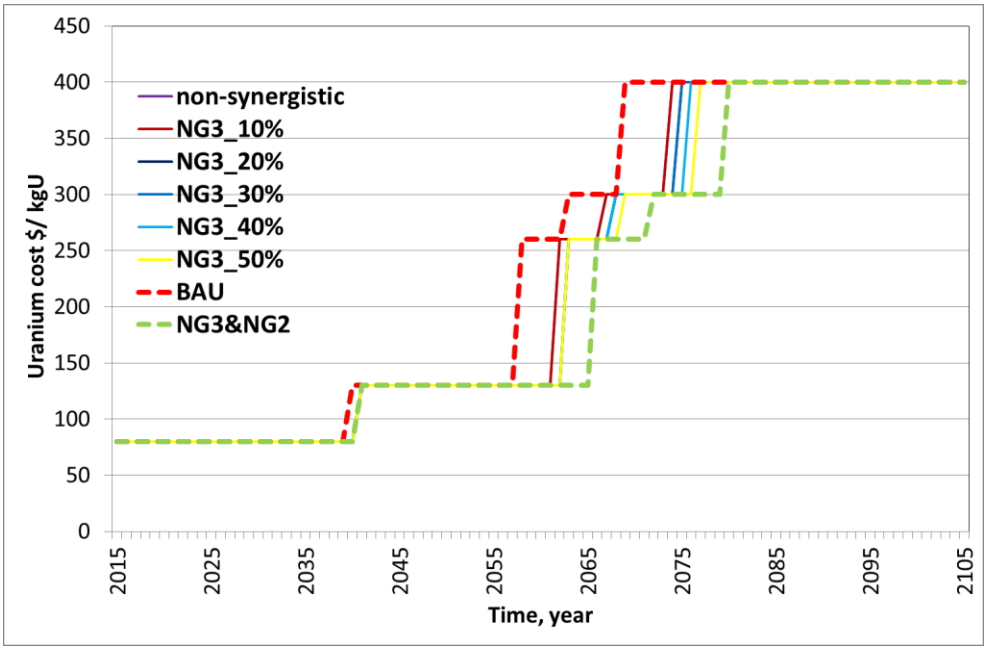

FIG. XIV-45. Natural uranium cost perspective versus uranium exhausting.

In BAU case, all identified and undiscovered resources of various costs that comprise 17.5 are exhausted by 2069. Transition from BAU option to BAU-FR separate world gives about 4 year shift to 2073. Collaboration with NG3 shifts the exhausting of identified and undiscovered resources on 3 year to 2076. Collaboration with NG2 and NG3 and high NG1 growth adds 4 additional years and shifts identified and undiscovered uranium exhausting to

2080. In sum, the possible maximum shift of identified and undiscovered resources exhausting is about 10 years. So, the transition from BAU option to BAU-FR synergistic option doesn't bring the essential impact on uranium cost in high scenario on short term and results in about 10 years shifting of identified and undiscovered resources exhausting on medium term. All countries can benefit from longer-lasting lower costs of natural uranium on long term.

XIV-3.7. Comparison of LUEC costs for LWR and FR technologies based on NEST tools

Comparison of levelized fuel cycle costs indicates that a LWR operating in once-through fuel cycle has the lowest fuel cycle component of levelized electricity generation cost (6.9 mills/kWh) of all reactors considered for reference fuel step costs and a cost of $80 per kg of natural uranium. Fuel component of electricity cost generated by an FR consuming its plutonium is 22% higher than in the case of LWR. The FR fueled by plutonium recycled from LWR spent fuel during its first three years of operation has the highest fuel components.

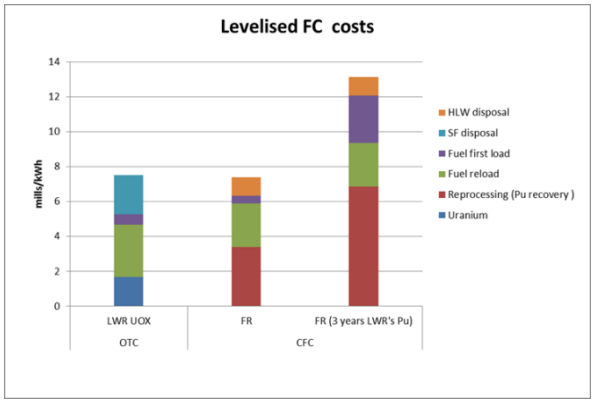

FIG. XIV-46. Levelized fuel cycle unit cost, U cost -=80 $/kg U.

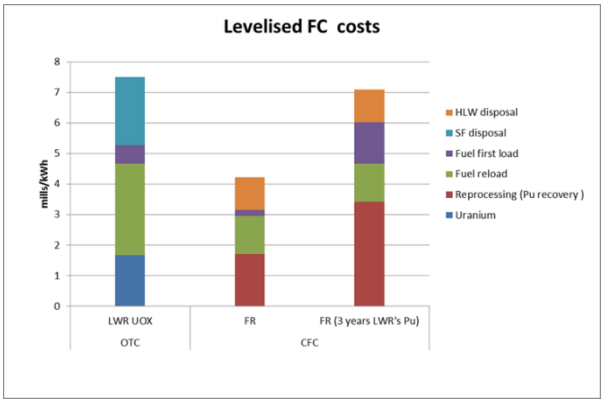

FIG. XIV-47. Levelized fuel cycle unit cost U cost -=80 $/kg U; MOX FF, SF Reprocessing costs reduced on 50%).

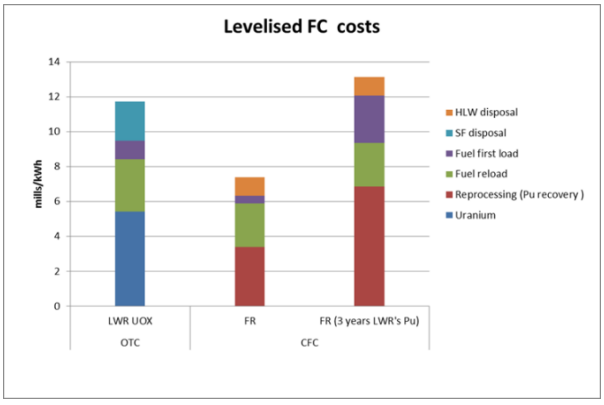

FIG. XIV-48. Levelized fuel cycle unit cost, U cost =260 $/kg U.

Therefore, the development of fast reactor programme in NG1 can face additional financial barrier as far as at first stage all new FRs must pass through a stage of rather expensive fuel fabricated from LWR plutonium. Factors that can change situation in favor of FRs are increasing of natural uranium costs and reduction of spent fuel reprocessing and

MOX fuel fabrication costs. In turn, the LWR fuel component increases as uranium cost moves higher whereas FR fuel cost doesn't depend on natural uranium cost. Fig. XIV-48 shows that at natural Uranium cost of 260 $/kg U (highest cost for identified and undiscovered grade 'd') and if reprocessing is done in large International center, FRs can be competitive with LWR. It should be reminded that the results are obtained for fuel cycle costs assuming equal capital and operation cost of reactors. If capital cost of FR is higher, the breakeven uranium cost will move to the even greater value.

So, the international center of reprocessing /fabrication can facilitate transition to the NES, based on FRs. Coupled with increasing of uranium cost it can enhance the economic attractiveness of NES coming to FRs.

XIV-4. ANNEX XIV SUMMARY

The results in Annex XIV show the impact of collaboration between groups on reactor mix and NFC infrastructure in NGs, under different group shares. Sensitivity analysis of NES scenarios using the GAINS framework has demonstrated quantitatively that a synergistic approach based on fast reactors could provide a significant potential for win-win collaboration between nuclear strategy groups and identify related issues:

- The synergistic case eliminates SNF accumulation and need of developing and constructing front-end and back-end fuel cycle facilities at NG3 which would benefit the NG3 strategy group. NG3 can avail NFC services from regional NFC centres at reduced expenses. However, there is an added issue of increased shipment of nuclear materials between the regional groups.
- Increase in NG3 share impacts NG1 reactor mix and results increase of fuel cycle front end requirements of enrichment and fabrication and the back end requirements of fuel storage reprocessing and ultimate disposal. Although increase in NG3 share reduces LWRs power production at NG1 but UOX fuel fabrication and SWU capacities at NG1 grow in order to facilitate increased fuel cycle requirements of NG3. NG1 can benefit from this scenario by deploying large scale fuel cycle facilities at earlier stages and providing fuel cycle services to other strategy groups at reduced price resulting from economy of scale approach.
- NG3 share at higher limits of above 40% causes stresses in NG1. Complete reprocessing of NG3 SNF cannot take place despite having sufficient fuel reprocessing capacity at NG1 since fast reactor introduction is limited by overall demand growth rate for NG1. On the other hand, significant reduction in long term SNF storage requirement is achieved by such synergistic cooperation.
- Minor actinide stocks in NG1 coming from NG3 increase with NG3 share growth and account for 10-30% of total MA accumulation in NG1 by 2100. Sustainability can be achieved by utilizing accumulated MA in a reactor or transmutation system.
- In the NG2-NG3 collaborative interaction scenario, stresses also appear in NG1 due to increased spent fuel loads. The NG1 power demand growth and reprocessing rate dictate the FR introduction rate and reprocessing capability of NG1 to reprocess SNF from all NGs. A part of SNF from NG2 and NG3 has to be stored and/or disposed of at their own facilities. Increasing the breeding ratio of FRs at NG1 will further intensify the SNF accumulation issue. The problem can be resolved by FR introduction in NG2 and/or NG3 without associated fuel cycle.
- Considering high energy demand growth and improved reprocessing capacities at NG1 can completely consume SNF from NG2 and NG3 by 2070, thus providing a valuable solution to global SNF accumulation issue using appropriate global synergistic

collaboration options. NG1 can develop and deploy large scale reprocessing centres and reduce the reprocessing costs for the region due to economy of scale.

- The investigation of uranium cost perspectives shows that the transition from BAU option to BAU-FR synergistic option doesn't bring the essential impact on uranium cost in high scenario, on short term, and results in shifting of identified and undiscovered resources exhausting on about 10 years, on medium term. All countries can benefit from longer-lasting lower costs of natural uranium in long term.
- The international center of reprocessing /fabrication can facilitate transition to the NES, based on FRs. Coupled with increasing of uranium cost, it can enhance economic attractiveness of NES coming to FRs.

Some intermediate results of study were presented at GLOBAL- 2013 [XIV-7].

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•

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