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REGIONAL AND WORLD LEVEL SCENARIOS FOR SODIUM FAST REACTOR DEPLOYMENT

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ABSTRACT

The revival of interest towards fast neutron reactors is due to their capability of producing more fissile material than they consume and reducing the burden on the disposal of high-level waste containing very-long life nuclides. Several studies on the impact of transition scenarios have been launched by international and national organizations. They show that the relevance of transitioning to fast reactors depends on the expected future role of nuclear energy and on the development of advanced nuclear technologies.

The purpose of the present study is to investigate the maximum deployable capacity of fast reactors at European and world levels mainly from the viewpoint of natural uranium and plutonium availability and energy demand projections. The calculations were performed with the DESAE code.

The results show that the maximum deployable capacity of fast reactors at European level is not limited by the plutonium and uranium availability with a reprocessing capacity of 3000 t/yr, whereas in the global scenario it strongly depends on the availability of uranium resources and plutonium stockpile.

1 INTRODUCTION

With an almost constant or slowly increasing of nuclear energy demand, the LWR technology can cope with the electric energy request at present rate of natural uranium consumption for some centuries, unless other criteria are taken into account, such as for example plutonium and/or waste minimisation [1]. Instead with a significant expansion of nuclear power due to the nuclear renaissance and/or policy in several countries, the security of natural uranium resources may be not assured after 2100 [1, 2]. The use of fast reactors becomes necessary, because they offer better performance than thermal reactors in terms of their capability in recycling and producing more fissile than they consume. Furthermore fast reactors allow to “burn” minor actinides, so reducing the waste amount and radiotoxicity, as well as the heat load on the final repository, and therefore the burden on the disposal of high-level waste containing very-long life nuclides.

Several studies have been launched by international organizations (IAEA, NEA, EU) and national institutes on the impact of alternative scenarios to LWR once-through fuel cycle. The outcomes of these studies show that the relevance of transitioning to fast reactors depends on the expected future role of nuclear energy and on the development of advanced nuclear technologies, which in their turn depend on R&D programmes undertaken within national and international framework. The choice of a scenario at country, region or world level must be done with a holistic approach that takes into account different parameters: efficiency of natural resource utilization, security of supply, radioactive waste management, infrastructure requirements and capabilities and duration of transition period [3, 4, 5, 6, 7].

The scenarios assessed in the present study are aimed at investigating the potential of innovative sodium-cooled fast reactors in satisfying the conditions for a sustainable development at European and world level during the present and next century. They foresee the transition from the current LWRs to ALWRs in a first phase and to sodium fast reactors in a second phase. The calculations have been performed with the DESAE code, developed in the frame of IAEA-INPRO project by Kurchatov Institute [8].

The paper deals with the results of the reference scenarios assessment and the sensitivity analysis performed in order to evaluate the impact of some parameters (SFR share, deployment timing, reprocessing capacity, SNF cooling time and breeding ratio).

2 REFERENCE TRANSITION SCENARIOS

The assessed scenarios at regional and global level foresee the transition from the current LWRs to ALWRs in a first phase and to sodium fast reactors in a second phase.

2.1 Regional and global scenario description

The regional scenario refers to a limited number of EU countries[1] with a fleet of 120 nuclear power plants and a total installed capacity of about 120 GWe. Two reference energy demand trends, shown in Table 1, have been hypothesized referring to the electric energy capacity projections developed by international organisations (NEA and IAEA) for the low scenarios [9,10]:

- Case **R-1** - constant electric energy demand. It refers to the “rationale” of NEA scenario, where the energy demand is almost constant up to 2050. As the NEA forecast is limited up to 2050, we have hypothesized to extend the projection “rationale” after 2050, i.e. we have considered the energy demand in the European countries still constant and the increase of energy capacity localized in other regions;
- Case **R-2** - increasing electric energy demand. It assumes the “rationale” of the IAEA INPRO scenario that hypothesizes an increase of the total energy consumption after 2030 with a nuclear share equal to its current level.

Also the global scenario (Case **G-1**) refers to the “rationale” of IAEA-INPRO low scenario and the corresponding projections are shown in the same Table 1.

Table 1 : Regional and global scenarios: nuclear capacity projections (GWe)

Case	1980	2000	2010	2030	2050	2100	2150
R-1	0	120	120	120	120	120	120
R-2	0	120	120	120	180	270	270
G-1	0	372	372	500	1000	2500	2500

To satisfy the energy demand the following assumptions for all scenarios have been made:

[1] Belgium, Bulgaria, Czech Republic, Finland, France, Germany, Hungary, Spain, Sweden and Switzerland.

a) the deployment of current LWRs starts in 1980 with a pace of 6 GWe/yr at regional level or 18.6 GWe/yr at global level. At the end of their lifetime they are replaced by ALWRs up to 2040;
b) ALWRs and MOX-fuelled SFRs are deployed from 2040 to 2100 according to the energy demand and LWRs replacement;
c) Only SFRs are deployed after 2100.

2.2 Hypotheses and assumptions

The following hypotheses and assumptions have been considered:

- The scenario covers about two centuries; the reference period is: 2000 – 2150;
- Both for regional and global scenarios the countries are considered as an indistinct whole in which all the resources (natural uranium, plutonium, spent fuel) and fuel cycle facilities (fabrication, enrichment and reprocessing) are shared among them;
- In the reference regional scenarios 1/3 of the total electricity demand will be warranted by SFRs deployment [11];
- Average LWR has been defined so that to be representative of current nuclear world fleet, whose 91% of the total installed capacity is produced by light water reactors (66% PWRs and 25% BWRs);
- Plutonium recycling in LWRs and ALWRs has been neglected, as nowadays the fraction of reactors fuelled with MOX is equal to 5%;
- UOX fuel discharged from LWRs/ALWRs is sent to the interim storage[2] and then reprocessed. Plutonium and depleted uranium coming from reprocessing plants are used for fabrication of SFR fuels;
- All the minor actinides produced by the reactor fleet are not recycled in SFRs and are directly sent to disposal together with fission products;
- According to the last Red Book [12], the currently known world uranium resources (identified[3] + undiscovered), equal to about 15.969 million tonnes[4], has been considered as “limit” for the uranium availability at regional and global level;
- Current reprocessing capability for LWR fuel has been assumed equal to 2600 t/yr at European level and 3800 t/yr at world level [13];
- Tail assay for ^{235}U enrichment has been assumed equal to 0.2%.

2.3 Nuclear systems description

Two types of LWRs have been considered in this study: pressurized LWRs conventionally representing all the regional and world fleet and pressurized ALWRs, characterized by a high burn-up and a high thermodynamic cycle efficiency. The values of the main reactor parameters are shown in Table 2.

The reference sodium-cooled reactor (SFR-R) is slightly breeder. Its BR is close to one. The values of its main parameters are reported in Table 2. In the sensitivity analyses an advanced sodium-cooled reactor (SFR-A) with a high breeding ratio has been also considered. Its main parameters are shown in the same Table 2.

[2] the SNF cooling times are reported in Table 2

[3] the total identified uranium resources (reasonable assured and inferred) amount to about 4456000 t in the < USD 80/kgU category and 5469000 t in the < USD 130/kgU category, whereas the undiscovered resources are more than 10500000 t; consequently the value considered as limit represents the resources with the highest extraction cost.

[4] neglecting the resources coming from phosphates and seawater

Table 2 : Basic reactor parameters

Parameter	LWR	ALWR	SFR-R	SFR-A
Reactor Unit Capacity (GWe)	1	1.5	0.9	1.8
Heavy nuclei load (t)	80	135	64	120
U235 enrichment (%)	4	4.9	0.2	0.2
Burn-up (GWd/t)	45	60	65	140
Natural uranium consumption (tU/GWe*yr)	180	150	-	-
Excess fissile Pu production (Kg/GWe*yr)[5]	-	-	40	295
SNF cooling time	5	3	3	3
Plant lifetime (yrs)	50	60	60	60

3 DESAE CODE

The scenario analyses were performed with DESAE code developed by the Kurchatov Institute in support of the IAEA-INPRO project activities [8].

The code allows the assessment of the resources, both financial and material, needed for a fleet of reactors to meet a specified nuclear energy supply projections at country, regional and global level.

The code performs material flow analysis based on a user-defined deployment scenario of reactors and fuel cycle facilities. It allows to model both open and closed fuel cycles (U-Pu, U-Th, Pu-Th and other combinations) including recycling of U and Th. The code is not able to perform burn-up or core management calculations and it bases its results on a database of fresh, equilibrium and spent fuel compositions, provided by the user for the different types of reactors. The fuel composition is followed for 17 isotopes, i.e. ^{232}Th, ^{232}U, ^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{237}Np, ^{242m}Am, ^{244}Cm, ^{129}I, ^{99}Tc, with one additional group for the other fission products. The code also calculates integral and differential consumption of different materials, e.g. Fe, Cu, Al, Zr. For fast reactors the core and blankets (axial and radial) are considered separately to take into account their isotopic compositions and cooling time before recycling.

The code allows to model seven reactor types at the same time, each one having its own fuel exchange path to be defined by the user. The fuel cycle may be represented with four fuel cycle facilities, without tracing losses in these facilities. The quantity of fission products and decay heat in spent fuel is calculated, but repository needs are currently only defined by the volume of materials to be stored.

The economic analysis with DESAE is limited to the evaluation of the required investment, net present value of investment and current cost of electricity, based on the capital costs of reactors and fuel cycle facilities, the operation and maintenance costs and the calculated fuel cycle costs.

4 RESULTS

The analysis has been aimed at investigating the maximum share of SFRs consistent with a sustainable development and the reprocessing plant capacity. To this end a comparison with once-through fuel cycle results has been performed and some parameters (SFR share, deployment timing, reprocessing capacity, SNF cooling time and breeding ratio) have been modified in order to investigate their impact on the results.

[5] It is an output of the code and represents the difference between the production and consumption of plutonium related to an year operation and a power of one GWe.

4.1 Regional scenario results

In the open fuel cycle the cumulative uranium consumption at year 2150 is equal to 3.07 and 5.22 million tonnes in the R-1 and R-2 scenario, respectively. In both cases it is lower than the total identified uranium resources[6] [12]. The total spent fuel mass to be stored in the deep geological repository amounts to about 0.37 million tonnes for R-1 and 0.63 million tonnes for R-2 scenario. As shown in Table 3, the SFR-R deployment allows to reduce the pressure on uranium resources. In fact, at increasing of the SFR-R share, the consumption of natural uranium decreases; in particular for both scenarios it is smaller than value of the total identified uranium resources related the <USD 80/kgU category. Instead the R-2 scenario is not sustainable from the plutonium availability point of view, as the amount of plutonium necessary for SFR-R deployment is insufficient. With an increase of the reprocessing capacity from 2600 to 3000 t/yr, the plutonium amount is always positive, as shown in Table 3.

Table 3 : Regional scenarios - Uranium and fissile plutonium balance

Deployment date	SFR-R share (%)	U_{nat} cumulative consumption at 2150 (t)		Minimum plutonium amount[7] (t)	
		R-1	R-2	R-1	R-2
2040	33	1.59E+06	2.37E+06	427	496 (2040)
	40		2.28E+06		496 (2040)
	66		1.95E+06		359 (2055)
	80		1.78E+06		278 (2056)
	95		1.59E+06		186 (2056)
2060	33		2.64E+06		291 (2117)
	95		2.38E+06		242 (2114)

Figures 1 and 2 show the annual installed electric capacity in the reference R-1 and R-2 scenarios, in which the SFR-R share is equal to 33% from 2040 and only SFRs are deployed after 2100. Both reference scenarios are sustainable having always available the necessary amount of plutonium for the SFR-R core fuel loading: the former with the current reprocessing capacity, the latter with a capacity of 3000 t/yr. Furthermore the R-1 and R-2 scenarios are still sustainable at increasing the SFR-R share, (see Table 3).

A 20 years deployment delay provokes a lack of plutonium amount for the fabrication of SFRs fuel to cope with the steep share at 2100, under the current reprocessing capability. It is sufficient to increase the reprocessing capacity by 400 t/yr to have again a positive excess of plutonium amount, (see Table 3).

Also a scenario characterized by a ALWRs fraction different from zero in the period 2100-2150[8], (see Figure 4), has an excess of plutonium production still positive (10 t) with the current reprocessing plant capacity and a cumulative uranium consumption of 3.05 million tonnes. The SFR-A deployment instead requires to increase the reprocessing capacity from 2600 t/yr to 3800 t/yr: the excess of fissile plutonium moves from -4786.31 t to 302 t.

[6] In particular in the R-1 scenario the uranium consumption is lower than the amount of the total identified uranium resources related the <USD 80/kgU category

[7] The values refer to a reprocessing capacity of 3000 t/yr; in brackets the year when the minimum value is attained

[8] In that period SFR-R plants replace 40% of ALWRs

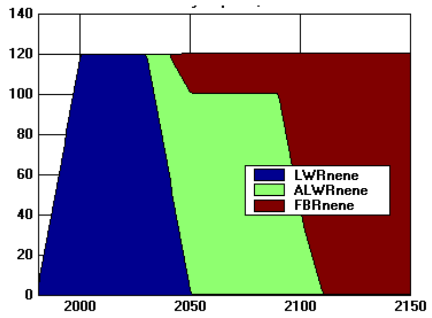

Figure 1: R-1 Annual installed capacity (GWe) for a 33% SFR-R share up to 2100

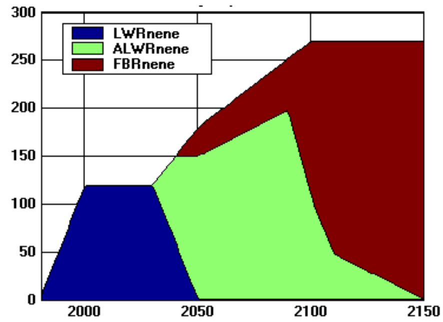

Figure 2: R-2 Annual installed capacity (GWe) for a 33% SFR-R share up to 2100

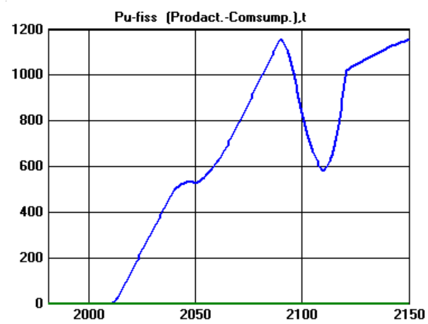

Figure 3: R-2: Production- consumption of fissile Pu for a 33% SFR-R share up to 2100

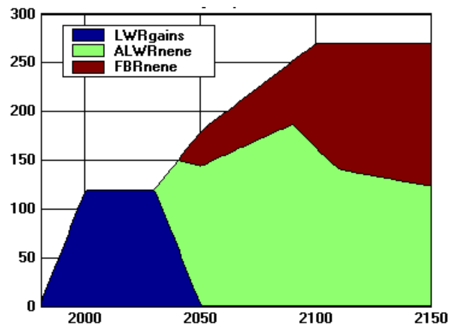

Figure 4: R-2 Annual installed capacity (GWe) for a 40% SFR-R share up to 2150

4.2 Global scenario

With the current world reprocessing plant capacity of 3800 t/yr, the adopted G-1 scenario is not sustainable due to the plutonium shortage, (see Table 4). Also the cumulative uranium consumption can be beyond the currently known world uranium resources depending on SFR share.

With a SFR-R share of 40% the uranium consumption is nearly equal to the known world uranium resources and the scenario becomes sustainable only if the reprocessing capacity is increased by at least 7 times, Figure 5. Instead the SFR-A deployment requires higher reprocessing plant capacity (about 15 times the current one) and investment.

Assuming a reprocessing capacity that gives positive plutonium balance[9], the consequences of a reduction in SNF cooling time are shown in Table 5, where the plutonium balance at year 2150 is reported for two assessed SFR options. The cooling time reduction has a strong impact on plutonium inventory and therefore it has to be carefully chosen for optimizing the scenario from the economic point of view.

Table 4 : G-1 scenario - uranium and fissile plutonium balance at year 2150

SFR-R share (%)	U_{nat} cumulative consumption (t)	Minimum plutonium amount (t)
5	20.53E+06	-5.27E+04
33	17.02E+06	-6.53E+04
95	7.23E+06	-10.44E+04

[9] 25,000 t/yr for SFR-R and 55,000 t/yr for SFR-A

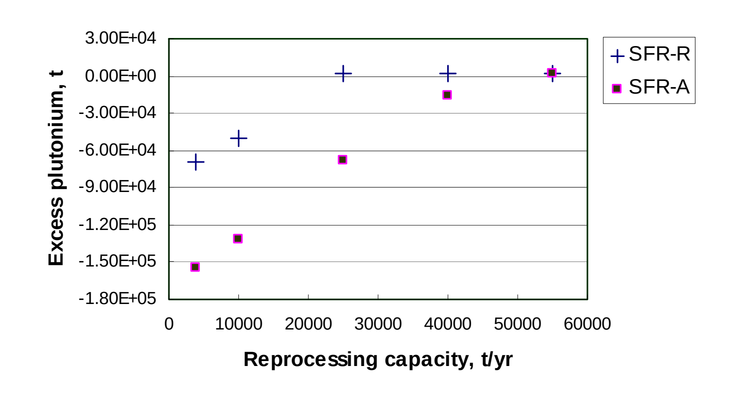

Figure 5 : Minimum fissile Plutonium excess vs reprocessing capacity

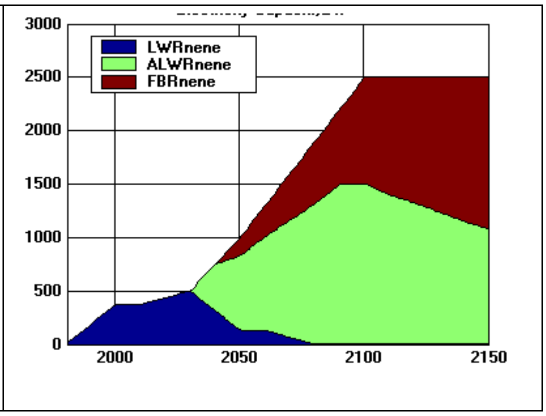

Figure 6 : G-1 Annual installed capacity (GWe): SFRs share = 40% up to 2150

Table 5 : Fissile plutonium balance at year 2150 (t)

SNF Cooling time (yrs)	SFR-R	SFR-A
3	0.53E+04	1.63E+04
2	0.68E+04	1.97E+04

A change of the policy in the scenario G-1, Figure 6, which foresees a SFR-R share of 40% up 2100 and a fraction of ALWRs different from zero[10] in the period 2100-2150, leads to a non-sustainability of the scenario, even if the plutonium amount is positive, as the cumulative uranium consumption is greater than the currently known world uranium resources.

A delay of 20 years in the SFR-R deployment leads to an increase of the U_{nat} consumption and plutonium amount, see Table 6.

Table 6 : G-1 modified - Uranium and fissile plutonium balance (t)

Deployment date	U_{nat} cumulative consumption (t)	Minimum plutonium amount (t)
2040	20.75E+06	0.23E+04
2060	24.05E+06	0.42E+04

5 CONCLUSIONS

The analysis performed, oriented to investigate the maximum deployable capacity of fast reactors at European and world levels mainly from the viewpoint of uranium and plutonium availability and energy demand projections, shows that:

- at regional level the R-1 and R-2 scenarios are sustainable: the former with the current reprocessing capacity, the latter requires an increase of the reprocessing capacity;
- at world level the reference scenario is sustainable only if the energy produced via SFRs is at least 40% of the total share and the construction of new reprocessing plants is planned;
- It is worth underlining that some benefits can be obtained by reducing the spent fuel cooling time.

[10] See note 8

ACRONYMS

ALWR	Advanced Light Water Reactor
BR	Breeding Ratio
BWR	Boiling Water Reactor
DESAE	Dynamic Energy System –Atomic Energy
EU	European Union
IAEA	International Atomic Energy Agency
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
LWR	Light Water Reactor
NEA	Nuclear Energy Agency of OECD
PWR	Pressurized Water Reactor
SFR	Sodium-cooled Fast Reactor (-R: Reference ; -A: Advanced)
SNF	Spent Nuclear Fuel
Unat	Natural uranium

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