Innovative systems for sustainable nuclear energy generation and waste management

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Innovative systems for sustainable nuclear energy generation and waste management

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Abstract: The limited amount of fossil resources, the impact of green-house gas emissions on the world climate, the rising demand of primary energy projected to 2050, lead to a potentially critical situation for the world energy supply. The need for alternative (to fossil energies) massive energy production is evaluated to 10 Gtoe. The potential of Nuclear Energy generation at the level of 5 Gtoe is examined. Such a sustainable production can only be met by a breeder reactor fleet for which a deployment scenario is described with the associated constraints. Waste management is discussed in connection with different nuclear energy development scenarios according to the point in time when breeder reactors are started. At the world level, it appears that the optimal handling of today’s wastes rests on an early decision to develop tomorrow’s breeder reactors.

1. Introduction

The societies of developed (and also of developing) countries make intensive use of energy and their way of life makes them extremely dependent on energy supplies (urbanization, comfort, industry, and worldwide transportation). This considerable amount of energy comes mainly from limited fossil resources (oil, gas, coal). The peak production of oil & gas is expected to happen within 10 to 30 years while the coal reserves are estimated to cover only 200 years of consumption at the present rate.

Meanwhile, a 50% increase of the world population is anticipated by 2050. Moreover, the per capita mean energy consumption is growing rapidly in developing countries (China, India, etc) while the developed countries see their energy consumption continue to grow. The predicted climate changes due to Green house Gas Emissions (GGE) lead to additional and immediate constraints.

The threat on our model of developed societies is severe. The present world organization is based on a “free” market and a more or less free access to energy resources, even though they are limited. The energy dependence of developed societies, the climate changes due to GGE, the fact that solutions have to be elaborated and applied at the world level, all these elements make the almost immediate future quite problematic.

The threat is so immediate that it is highly probable that in 2050 the energy crisis will be stabilized either by an adequate worldwide energy policy, or by catastrophic events reducing significantly the energy demand itself!
Quantitatively the energy demand will grow by at least a factor of 2 from 2000 to 2050. At the same time, we have to reduce GGE by a factor of 2, and to face a crunch on some fossil resources. It is crucial, then, to examine the ways in which the generation of massive amounts of energy, at the level of at least 10 Gtoe/year, could be achieved in a sustainable way.

In this paper we present an analysis of the potential of nuclear power in relation to the objective of producing 5 Gtoe by 2050, representing 25% of the world total primary energy.

A somewhat widely shared opinion in the public of developed countries argues that the energy crisis could be avoided by reducing their own energy demand. But this proposition is not convincing for 2 reasons: first, the absence of economic incentives to do that precisely in developed countries, second, the fact that the growth of energy demand will come mainly from developing countries and the additional 3 billion people in the world population in 2050. So we have to be realistic and quantitatively logical!

2 The world energy context.

2.1 Energy consumption and fossil fuel reserves.
The total global energy consumption of primary energy in 2000 and its break down among the different energy sources is shown in Table 1.

This table shows that 75% of the 10Gtoe consumption in 2000, is provided by fossil fuels At present, 50% of the total energy is consumed in OECD countries, which represent 20% of the world population [1]. These countries are not at all headed towards significantly reducing their energy demand, which grows by more than 1% per year. In the next decades, by 2050, the world population will increase by 50% (6 billion in 2000 and 9 billion in 2050), while very important developing countries will multiply their per capita energy demand by a factor of 2 to 3. The IEA and other international institutions have set up various scenarios. The predicted increase between 2000 and 2050 varies from 1.5 to 3. Let us note that a 1.5 increase implies that the per capita energy consumption would stay constant!!

2.2 Green house gas emissions and climate change.
The massive use of fossil fuels is responsible for the emission of large quantities of green house gases, CO₂ and methane. It has been demonstrated that this massive emission induces global warming of the earth’s climate, a mean temperature increase of 0.6°C having already been observed. Climate model studies show that the temperature increase could be stabilized to 2°C if we were to reduce the GGE by a factor of 2 over the next 50 years. The climate change issue appears so huge and urgent that humanity cannot wait for the exhaustion of fossil fuel reserves to limit their consumption. In summary, we have to simultaneously, - face the already mentioned reduction of available fossil fuel - drastically reduce GGE and adapt our way of life to the climate changes already engaged and, in addition, to deal with the population growth and the legitimate growing per capita demand in developing countries.

Maximal per capita emissions for a 6 Billion population, in order to stabilize the CO₂

Figure 1 Tons of Carbon / capita /
2.3 Choice of a mean scenario

In order to evaluate the contribution of each energy source in 2050, we selected a scenario in which the energy demand satisfied in 2050 is twice the 1998 energy consumption. Table 1 presents the 1998 contributions of each energy source.

| Source                          | 1998 World total consumption in Gtoe | 2050 Scenario x2 in Gtoe |
|---------------------------------|-------------------------------------|--------------------------|
| Fossil (Gas, oil, Coal)         | 7.5                                 | 7.5                      |
| Traditional biomass             | 1.2                                 | 1.2                      |
| Hydraulic                       | 0.7                                 | 1.0                      |
| Nuclear                         | 0.6                                 | (5.15)                   |
| New Renewable Solar, Wind, Biomass | 0.02                          | (5.15)                   |
| Total                           | 10.02                               | 20.04                    |

Table 1: Contributions of each energy sources in 1998 and projected in 2050

The evaluation of the 2050 contributions, are based on the following ideas:
A) Due to the fast increase of energy demand and GGE constraints, we suppose that the fossil contribution will stay roughly constant** along with the conventional biomass while hydraulic power increases moderately.

B) By difference, we see that 10 Gtoe of primary energy have to be found by 2050, using “New Renewable Energies” (NRE) and Nuclear Energy (NE). The potential of NRE based on Solar Energy (Thermal Solar, Photovoltaic, Wind, commercial Biomass) is limited due to their dispersion, intermittent character, price and/or climate and soil limitations. Nevertheless, to be conservative, we supposed that NE and NRE will contribute equally to the primary energy supply increase in 2050, namely 5 Gtoe each.

In the following sections we present the potential of present technology for such a NE generation in 2050, as well as the potential of breeder reactors for sustainable NE generation and waste management. We will show also how NE generation can be technically deployed to reach a production of 5 Gtoe in 2050.

The break down between fossil energies, new renewable energies and nuclear energy generation may depend on economic factors, choice of societies, new technologies for CO2 sequestration. However, for the moment, our choice of 5 Gtoe for NE generation seems to us a conservative estimate if we really want to solve the energy issue!

** We suppose that the constant fossil energy consumption is compatible with a reduction of GGE by a factor 2 thanks to large scale CO2 sequestration

3 Present nuclear technology, potential and limits

At present 6% (0.6 Gtoe) of the 10Gtoe world’s primary energy consumption comes from nuclear fission reactors. If NE represents 25% of the total primary energy in 2050, the nuclear power generating capacity has to be multiplied by a factor 8 in the next 50 years.

Present reactors are mainly based on the use of 235 Uranium which is the only fissile nucleus present in nature (0.7% of natural uranium). The annual uranium ore consumption is around 180 tons per Gwe-year. The world reserves which are estimated  to 16 million tons represent around 300 years of nuclear energy generation at the present rate. Obviously they cannot ensure sustainable energy generation if NE is to contribute significantly to the world’s energy needs.

Moreover, besides the ethical issue raised by the use of a very large part of the $^{235}\text{U}$ reserves, the LWR (Light Water Reactor) fuel cycle would not be closed and would be accompanied by a large amount of radiotoxic spent fuel containing large quantities of Plutonium and MA (with long lifetimes) as indicated in Table 2. This aspect will be discussed further in the waste management section.

| $^{235}\text{U}$ ($T_{1/2}=4.4\ 10^9\ y$) | 25 655 kg | Fission fragments mean lifetime $T_{1/2}\leq 30\ y$ | 43Kg |
| $^{235}\text{U}$ ($T_{1/2}=7.04\ 10^8\ y$) | 280 kg | mean lifetime $T_{1/2}\leq 30\ y$ | 43Kg |
| $^{236}\text{U}$ ($T_{1/2}=2.34\ 10^7\ y$) | 111 kg | Fission fragments |
239Pu (T1/2=2.41 $10^4$ y) 156 kg long lifetime 63Kg

Total Pu 266 kg Fission fragments Total 946Kg

Table 2 Composition of LWR spent fuel for 1Gwe-year

4 The problematic of Breeder Reactors

4.1 Neutron physics constraints for breeder reactors

4.1.1 Breeding conditions

In a breeder reactor the $^{235}$U is no longer used. The fissile material is made in the reactor itself from the main elements of U and Th ores, i.e. $^{238}$U and $^{232}$Th, using the following reactions in the reactor. $^{238}$U + n $\rightarrow^{239}$U $\rightarrow^{239}$Np $\rightarrow^{239}$Pu fissile or $^{232}$Th + n $\rightarrow^{233}$Th $\rightarrow^{233}$Pa $\rightarrow^{233}$U fissile

In such reactors, only the $^{238}$U and $^{232}$Th, called fertile elements, are consumed. The potential of NE generation using breeder reactors is 1Gwe-year per ton of U or Th ore, which is 180 times more than for the LWR present technology, and solves the problem of sustainability.

However, in such breeder reactors, the neutron economy is tighter due to the use of at least one neutron per fission to transform a fertile nucleus into a fissile nucleus. We also will have to consider how a reactor fleet based on such reactors can be deployed since neither $^{233}$U nor $^{239}$Pu are to be found in nature.

Neutron economy aspects and fissile inventories

In a fission chain reaction we have the following reactions, e.g. with plutonium:

$\nu$ + $^{239}$Pu $\rightarrow$ fission + $\nu$ neutrons

where $\nu$ is the mean number of neutrons emitted per fission, and

$\alpha$ n + $^{239}$Pu $\rightarrow^{240}$Pu (capture reaction on a fissile nucleus) where $\alpha= (\sigma_{\text{capture}}/\sigma_{\text{fusion}})$ fissile

Thus, each fission consumes $(1+\alpha)$ neutron. We need $(1+\alpha)$ n + $^{238}$U $\rightarrow^{239}$Pu (capture reaction on fertile nucleus) to replace the mean quantity of fissile nuclei consumed per fission.

Then we have the constraint: $N_a= \nu - 2(1+\alpha)$ >0 where $N_a$ is the number of available neutrons for over-breeding, unavoidable parasitic reactions and neutron losses. For a given neutron energy $N_a= \nu(E) - 2(1+\alpha(E))$. This means that the breeding condition depends on the fissile nuclei cross sections.

Fig 2-1 shows the variation of $N_a$ versus neutron energy for Uranium and Thorium based fuels. The breeding condition is satisfied only with a fast neutron spectrum in the case of the Uranium based fuel, while both fast and thermal neutron spectra satisfy the condition for a Thorium based fuel.

4.1.2 Inventory constraints

![Fig 2-2C](image)

$N_a=\nu(E) - 2(1+\alpha(E))$ [where $\alpha=(\sigma_{\text{capture}}/\sigma_{\text{fusion}})$ fissile]

Fig 2-2C: $\sigma_{\text{capture}} / (\sigma_{\text{capture}} + \sigma_{\text{fission}} + \sigma_{\text{fusion}})$
a) Writing that for each fission, \((1+\alpha)\) fertile nuclei are consumed, it is easy to show that the fissile element concentration in the fuel is

\[C = \frac{M_{\text{fissile}}}{M_{\text{fissile}} + M_{\text{fertile}}} = \frac{\sigma_{\text{capt-fert}}}{\sigma_{\text{capt-fert}} + \sigma_{\text{capt-fiss}} + \sigma_{\text{fission-fiss}}}\]

where \(\sigma\) stands for the cross sections averaged over the neutron spectra. We observe that this concentration depends only on neutron cross-sections of fissile and fertile elements. The neutron energy dependence of the fissile material concentration has been plotted for the Th and U fuel cycles in fig 2-2.

Figures 2-1 and 2-2 show the main characteristics of the two fuel cycles, U-Pu and Th-U. We mentioned that the U-Pu fuel cycle can be breeder only in a fast spectrum or, more precisely, for neutron energies greater than 50 keV while the Th-U fuel cycle can be breeder in both a thermal and a fast spectrum. The fissile concentrations in the fuel are quite similar, around 10 to 12% for the two fuel cycles considered in a fast spectrum and about 1.5% in a thermal spectrum (which concerns only the Th-U fuel cycle).

b) The fuel inventory depends also on the power density per cc that can be extracted from the fuel and on the fuel/coolant thermal properties. For example, in a fast breeder reactor using U-Pu oxides as fuel, a value of 500 W\text{thermal}/cc is usually retained for a liquid metal coolant (sodium or lead) and only 200 W\text{thermal}/cc for a gas coolant. With this limitation we can easily have a good idea of the fuel and fissile inventories per unit power. For a 1 GWe power and a conversion factor of 0.33, we obtain for a fast neutron spectrum and solid fuel \(m_{\text{fuel}}\) (in tons) = \(10^7 \times d/(500*0.33*10^6)\) = 60.6 tons and \(m_{\text{fissile}} = C \times \sigma_{\text{fissile}}\) = 6 tons where C, the fissile concentration and \(d\) the fuel density have been taken equal to 0.1 and 10 respectively. If we take the reprocessing constraint (see below), into account with a hypothesis of an equal time for fuel in and out of the reactor, the effective fissile inventory reaches 12 tons /GWe.

4.2 Fission fragment poisoning and reprocessing constraints:
In a breeder reactor the fission fragments, which stay in the fuel, consume neutrons and will jeopardize the breeding characteristics if they accumulate too much inside the reactor. The effect of FF poisoning is around 10 times larger in a thermal spectrum than in a fast spectrum. With solid fuels, fission fragments are extracted periodically. This implies removing the fuel from the reactor, chemical extraction of the FFs, and fabrication of new fuel assemblies. In liquid fuel reactors, specific reprocessing procedures are used and will be detailed in section 4-5 on Thorium molten salt reactors.

The net effect for solid fuels is that the total fissile inventory per GWe reactor is the sum of the mean amount of fissile element which is outside the reactor for fuel reprocessing and reconditioning and the fissile quantity inside the reactor. An obvious consequence is that breeder reactors require efficient and fast fuel reprocessing in order to minimize the fissile inventory.

We should specify that the fertile and fissile elements of the fuel are fully recycled as well as the MA if necessary so that the ultimate wastes are composed of FFs plus heavy element losses. In that case the fuel cycle is called “closed” and the long term radio-toxicity per GWe-year is reduced by factors of 100 to 10000 depending on the fuel cycle and the reprocessing losses.

4.3 Summary of breeder reactor constraints
A thermal spectrum allows a low fissile inventory, but requires more reprocessing capacity (which can have a negative impact on the fissile inventory) and the use of Th-U fuel is the only possibility.

A fast spectrum is convenient for breeder reactors using either U-Pu or Th-U fuels, but needs larger fissile inventories; the needed reprocessing capacity is roughly divided by 8 compared to a thermal spectrum at comparable power density.

Overall fissile inventories depend on the neutron spectrum (thermal or fast), on the power density which can be used and on the procedure related to the fuel reprocessing for FF extraction as this keeps fissile material outside of the reactor.

4.4 Fast Breeder reactor technologies using the U-Pu Cycle
The Generation IV international forum has retained three types of fast breeder reactors using the U-Pu cycle: sodium-cooled, lead-cooled and gas-cooled reactor concepts. This choice is based on solid fuels and coolants which do not moderate the spectrum too much. The sodium-cooled reactor has been largely experimented from small to full power reactor scale. This technology is considered as an ‘available today’ technology. Nevertheless the use of sodium places strong constraints on critical power reactors due the chemical properties of sodium and the presence of a large neutron absorption resonance which induces, in some cases, a positive void coefficient.
The lead coolant has been experimented in Russia using an eutectic Pb-Bi that has the advantage of reducing the fusion temperature. The liquid lead coolant has very good neutronic properties; the main difficulty is related to corrosion on structural materials operating above 600°C over several decades in a large reactor fleet. However, this technology could be used in dedicated incinerator reactors (Accelerator Driven Sub critical reactors) that would represent a few percent of the total fleet, as proposed first by C. Rubbia [2]. It is presently being studied in the frame of European programs. Gas-cooled fast reactors are an attractive technology due to the possibility of operating at high temperatures coupled with a direct use of the coolant in electricity conversion machines. The resulting conversion coefficient could reach 50%. The lower power densities which can be used, 200 Watts/cc instead of 500 Watts/cc, and their impact on in-reactor inventories can perhaps be compensated by an irradiation time of 15 years which is allowed by the low power density, the higher temperature and associated better thermal efficiency, and a reprocessing procedure which would not retain the fissile element outside of the reactor core more than 2 years. The resistance of structural materials to high temperatures, corrosion effects and adequate solutions to evacuate residual heat in case of normal cooling failure seem to be the main challenges of this technology.

4.5 Breeder reactors using Th-U233 Cycle with molten salt technology
As previously stated, breeder reactors using the Th-U cycle can operate with both thermal and fast neutron spectra. With a thermal spectrum the low inventory benefit is counterbalanced by the need for an efficient and fast FF extraction due to their already mentioned faster poisoning effect. A liquid fuel core concept has been studied to address this issue. The fuel is made of molten fluoride salts containing fertile and fissile elements, Thorium and 233Uranium. The liquid fuel allows on-line reprocessing. A typical composition of the salt is 78%LiF-22% (Th-U)F4.
In such a reactor the liquid fuel salt serves as both the coolant and the fuel.
The neutronic characteristics of such reactors using the Th-U cycle have been recently revisited [3],[4]. An extensive study of the following properties: breeding ratio, needed reprocessing capability, temperature coefficients, and graphite moderator life time, of such reactors based on Th-U, molten salts has been done in relation to various spectrum moderation factors. Although it is not the only possibility, the fastest spectrum which is obtained without any moderator in the core appears to be a very promising solution: the reprocessing constraints are flexible, the over-breeding is quite satisfactory, the temperature coefficients allow a stable and safe operation and the moderator life-time issue disappears. Thermo-hydraulic studies are currently in progress to determine if the impact on the fissile inventory due to the fast spectrum, can be reduced by increasing the power density or a decrease of Th-U concentration in the salt. Transitory power profiles in case of reactivity insertions are also under investigation.
The Thorium Molten Salt Reactor is characterized by much lower MA production and therefore a much lower radiotoxicity due to MA losses, compared to fast breeder reactors based on the U-Pu cycle. On-line fuel reprocessing allows a reduction of the fissile inventory by a factor 3 or 4 depending on the power density in the case of a fast spectrum, and a factor 8 in a more moderated spectrum compared to the U-Pu cycle using solid fuels. So the fissile inventory ranges from 1,5 to 4 tons per Gwe.
- Specific reprocessing aspects for molten salt fuels (fluorides)
We first consider the possible extraction of gaseous and noble metal fission fragments by a helium bubbling device. The second aspect is related to the easy and fast U extraction from the fuel by fluorination. This very peculiar U property is used in the following way: when a batch of fuel is extracted for reprocessing, the Uranium is first and quickly extracted and re-injected immediately in the reactor, thus minimizing the fissile mass outside of the reactor. Subsequent FF extraction and the actinides recovery for recycling can be slow.

4.6 Deployment of a sustainable NE generation : 5 Gtoe in 2050
The sustainability of NE production requires a nuclear reactor fleet based on breeder reactors. We already raised the problem of the fissile inventory needed to start a new breeder reactor. Over-breeding allows a doubling time of 40 to 60 years and does not help much for the 2050 target. In addition it is usually admitted that FBRs (Fast Breeder Reactors) could start in 2020 and TMSRs (Thorium Molten Salt Reactors) in 2030.
Let us consider a nuclear reactor fleet based on LWRs and FBRs. Since LWRs produce Pu, this Pu can be used to start FBRs, but the Pu inventory needed is 12 tons which is the amount produced by a 1Gwe LWR during its 40 years lifetime. Optimal Pu management allows to reach 5 Gtoe in 2050 with a reactor fleet composed of 70% LWRs and 30% FBRs as shown on fig 3-1.

If the breeder reactors are mainly Thorium molten salt reactors which have an $^{233}$U inventory of 3 tons per Gwe, we need less fissile material, but we have to transform the LWR Pu into $^{233}$U. This can be done in LWRs, and a small fleet of FBRs which also have the function of properly closing the LWR fuel cycle. We then end up with a three component fleet: LWR 12%, FBR 12%, TMSR 75% [5]. This solution allows a faster transition from the present situation to a full breeder reactor fleet, may have the advantage of consuming less Uranium235, of producing less MA and therefore minimizes the ultimate long term waste radio-toxicity. This deployment scenario is presented in fig 3-2.

Obviously a mix of the two deployment scenarios presented is conceivable, or other solutions can be considered. Nevertheless these scenarios illustrate the inventory constraints and also the necessary construction of a large number of LWR type reactors whose fuel cycle closing becomes a necessity.

**Figure 3-1: Deployment of the nuclear power fleet with LWR reactors and fast neutron reactors.**

**Figure 3-2: Deployment of the nuclear power fleet with light water reactors, FNRs and MSRs.**

5 Waste management, from the present situation to 2050 with different scenarios.

1. 5.1 Waste management problematic and possibilities

The radio-toxicity associated with the FF part of the waste is independent of the fuel cycle and of the reactor type (LWR, Breeder reactor with U or Th cycle). The characteristics of this waste (FF) is to have a strong component with a half-life of 30 years which means that after 600 years the associated radio toxicity is reduced by $10^{-6}$. After 600 years the remaining FF radio-toxicity is due to very long lived nuclei and stays on the order of one hundredth of the initial radiotoxicity of the fuel used for their generation in LWRs.

The other part of the radio-toxicity is due to the heavy elements present (U,Pu and MA) in the “ultimate wastes”. As shown on fig 4, for LWR spent fuels, the associated radio-toxicity is dominant after 600 years. The heavy element radio-toxicity is characterized by much longer lifetimes (200 to $10^6$ years).

At present, for the most part, about 80%, the world spent fuels are not reprocessed and the mass of LWR spent fuel is about 30 tons x Number of Gwe-year produced, although several countries reprocess part of their spent fuel. Although the reprocessing is only concerning 20% of the would spent fuel flux, the reprocessing procedure has been optimized and has proved its efficiency at a significant industrial scale. This reprocessing consists in extracting the uranium and Pu from the spent
fuel, leaving the non volatile FFs mixed with trans plutonium elements, i.e. minor actinides, as ultimate waste. Recently the scientific feasibility of minor actinide extraction and partitioning has been proved and we will suppose that industrial partitioning will soon be proved with $10^{-2}$ loss while the U and Pu extraction is done with a $10^{-3}$ loss.

Figure 4 Heavy nuclei radio-toxicities for LWR (LWR), U-Pu and Th-U3 fuel cycles[6]

| Waste/ Gwe-year | FBR U-Pu | TMSR Th-U3 |
|-----------------|----------|------------|
| U               | 4000g    | 1g         |
| Pu              | 600g     | 20g        |
| Am              | 200g     | 1.3g       |
| Cm              | 50g      | 5g         |

Table 3: Typical mass of heavy nuclei present in ultimate wastes for FBR U-Pu and Th MSR

So, now we have 3 options to consider: 1) no reprocessing, 2) reprocessing with extraction of U and Pu only, with ultimate wastes containing FF, 0.1% of Pu and 100% of MA, 3) reprocessing with U, Pu, MA extraction with ultimate wastes containing FF plus 0.1% of Pu and 1% of MA.

5.2 The scenario in which there is no breeder reactor decision

In such a situation, the radio toxicity of LWR spent fuel is dominated by the Pu contribution, but Pu extraction without having a possibility to burn it is of no use so that spent fuel reprocessing does not appear necessary. We could imagine Pu burning reactors but then we have to first decide, that we will never need breeder reactors. So spent fuel reprocessing at the world level cannot be decided prior to a decision on Breeder Reactors.

The present situation will probably continue, and most of the spent fuels will be put in temporary repositories, pending a decision for breeder reactors.

5.3 The scenario in which there will be breeder reactors (firm decision at world level)

In that case, the spent fuel reprocessing has to be decided at least for a part of it, in order to be able to deploy a breeder fleet. The optimal decision for the lowest radiotoxicity in ultimate wastes would be to extract U, Pu and MA. While U and Pu are reused in breeder reactors, MA could be incinerated either in ADSR type dedicated reactors [6], or in FBR reactor fleets, or they could be placed in dedicated containers for permanent or temporary storage.

5.4 Which waste management in the present situation and the forthcoming 10 or 20 years?

Let us examine the problem at the world level with an open mind:

First, the nuclear waste storage has to be internationally controlled and could be situated in few optimum geographical sites in the world. The LWR fuel reprocessing could also be organized and controlled at the world level and then the MA partitioning option could be chosen. In the same way, the possibility of MA incineration in dedicated reactors could be actively experienced to help the choice mentioned above and/or to ease the breeder reactor fleet operation.
But first, a clear commitment at the world level should be made concerning the breeder reactor and waste management necessity. If not, the risk is high to have a blocked situation where even the continuation of NE generation with the present technology could not be accepted in our societies. New ideas with few number of countries, which would handle internationally controlled reprocessing and fuel fabrication as well as ultimate waste storage are coming to light and may change the NE perception.

5.5 Conclusion on waste management options.

The solutions for optimal waste management depend on the future use of nuclear energy. It appears that breeder reactors can (if they are decided) close the fuel cycle of the LWR type reactors presently in operation and allow an optimal waste management: the Pu is used in new breeder reactors, the MAs can be incinerated. Quantitatively, the long term radio-toxicity of ultimate wastes per unit energy produced is reduced by a factor 100 or 1000 depending on whether the U or the Th fuel cycle is used. It appears also that the breeder reactor option, which guarantees the sustainability of NE generation at a significant level is a key point for opening the road towards an optimized civilian nuclear waste management.

Conclusion

After examining the world energy context dominated by the fossil fuel limitation coupled to very severe constraints on GGE to avoid potentially catastrophic climate changes, we estimated the world energy demand by 2050 to be at least 20 Gtoe compared to the 10 Gtoe in 2000. Since increasing the use of fossil energy becomes quite hazardous for human life, we are arithmetically condemned to find annually 10 more Gtoe by 2050 from either new renewable energies or nuclear energy generation. Obviously, new renewable energies have a limited potential which is not well quantified. So considering that NE should produce at least 5 Gtoe in 2050 appears to be a conservative estimate if we really want it to contribute significantly to the world energy demand in 2050. Behind this choice is the ethical assessment that recognizes the right of the populations of developed and developing countries to have access to a comfortable life. And this is conditioned by a free or equal and not too expensive access to energy. Nuclear energy generation is certainly able to provide such an amount of energy in a sustainable way with the use of breeder reactors. We saw also that 2 kinds of breeder reactors have to be considered for which some challenges are common and some are different. The road to reach such an ambitious goal is difficult, but it is our conviction that nuclear waste management options have to be cleared up by a rapid choice concerning breeder reactors, since they are able to close the fuel cycle of present technology reactors and allow sustainable energy generation. Delaying this choice for economic or political reasons is quite hazardous since NE could appear unable to reduce their waste production and unable to guarantee any sustainability. The consequence would probably be that NE generation at a significant level at the right time would be made very difficult. As a result, an energy shortage would be likely, GGE reduction could appear too difficult, and then we would have all the ingredients for a very dangerous situation with possible generalized conflicts.

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