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NUCLEAR ENERGY DEVELOPMENT IN THE 21st CENTURY: GLOBAL SCENARIOS AND REGIONAL TRENDS

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IAEA NUCLEAR ENERGY SERIES No. NP-T-1.8

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FOREWORD

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was launched in 2000, on the basis of a resolution of the IAEA General Conference (GC(44)/RES/21). INPRO helps ensure that sustainable nuclear energy is available in the twenty-first century and seeks to bring together all interested Member States — both technology holders and technology users — to consider joint actions to achieve desired innovations. As of July 2010, 30 countries and the European Commission are members of INPRO.

Programme Area B of INPRO, Global Vision — Scenarios and Pathways to Sustainable Nuclear Power Development, is aimed at providing a better understanding of the role of nuclear energy in the context of long term sustainable development. Its objective is to develop global and regional nuclear energy scenarios on the basis of a scientific-technical pathway analysis that lead to a global vision on sustainable nuclear energy development in the twenty-first century, and to support Member States in working towards that vision.

This report presents the results of a study undertaken under Programme Area B in INPRO on Nuclear Energy Development in the Twenty-first Century: Global Scenarios and Regional Trends Studies on Nuclear Capacity Growth and Material Flow between Regions.

The report does not develop a global vision for nuclear deployment per se, but presents a limited set of technical scenarios of nuclear deployment and considers their implications. It considers a global energy supply system composed of several reactor and fuel cycle types available today and of fast reactors that may be developed in the future to illustrate a possible modelling approach to identify the potential role of interregional transfer of nuclear fuel resources in supporting the global growth of nuclear energy. The study was performed with the participation of sixteen experts from nine INPRO Member States and included a dynamic simulation of material flows in nuclear energy systems using available nuclear power development modelling tools.

The results of the study will constitute one of the inputs for formulating an INPRO vision on global nuclear energy sustainability in the twenty-first century, together with the results of several other studies currently being carried out in the framework of INPRO's Programme Area B, including the INPRO Collaborative Projects on Global Architecture of Innovative Nuclear Systems based on Thermal and Fast Reactors including a Closed Fuel Cycle (GAINS) and Fuel Cycles for Innovative Nuclear Systems through Integration of Technologies (FINITE), Investigations of the 233U/Th Fuel Cycle (ThFC) and Meeting Energy Needs in the Period of Raw Material Insufficiency during the 21st Century (RMI).

The IAEA officers responsible for this publication were M. Khoroshev and V. Lysakov of the Division of Nuclear Power.

CONTENTS

SUMMARY

A reliable, accessible and affordable supply of energy produced in a sustainable manner is fundamental for the development of modern society. The future energy mix will be determined by the availability of technologies, life cycle generating cost, environmental and health impacts, security of supply and public acceptance. Nuclear energy has an important feature: it potentially provides a stable base load quasi non-CO_2 emitting source of energy that is readily available and can be deployed on a large scale to meet even fast growing energy demand. According to recent scenarios, global primary energy demand is expected to increase by a factor of 1.5–3 by 2050 compared with today, and 2–5 times by 2100. The relative growth in electricity demand will be twice as large.

Programme Area B of INPRO, Global Vision — Scenarios and Pathways to Sustainable Nuclear Development, is aimed at providing a better understanding of the role of nuclear energy in the context of long term sustainable development. Its objective is to develop global and regional nuclear energy scenarios on the basis of a scientific-technical pathway analysis, that lead to a global vision on sustainable nuclear energy development in the twenty-first century, and to support Member States in working towards that vision.

In the framework of Programme Area B in INPRO, a study was carried out on Nuclear Energy Development in the 21st Century: Global Scenarios and Regional Trends Studies on Nuclear Capacity Growth and Material Flow between Regions with the following objectives:

- To illustrate, using idealized examples, the potential contributions of innovative nuclear energy systems using fast reactors and closed fuel cycles to meet global and regional demands for nuclear energy. This is done for a range of possible demand scenarios;
- To illustrate the potential roles of different reactor types operating in combination in an evolving and growing global nuclear energy system;
- To illustrate, for a range of possible demand scenarios, how nuclear material might flow between different regions of the world in the twenty-first century;
- To identify some of the issues that might need to be addressed to implement the deployment of nuclear energy as presented in the study, in particular, for the two higher demand scenarios.

This report does not develop a global vision for nuclear deployment per se. It develops a limited set of technical scenarios of nuclear deployment and considers the implications thereof. The study considers several reactor and fuel cycle types — available today, and with potential to be developed in the future. Implications considered include the potential role of interregional transfer of nuclear fuel resources and also various potential constraints such as resource availability.

The INPRO methodology sets out criteria in seven areas — economics, infrastructure, safety, waste management, proliferation resistance, physical protection, and environment — that need to be satisfied for nuclear energy to be sustainable. It is assumed that the nuclear energy systems discussed in this report will be developed to meet these criteria. The study then illustrates how fast reactors and closed fuel cycles can limit the demand for uranium resources. A number of other assumptions have been made to facilitate the study. They have to do mainly with the need for nuclear energy and its substantial growth, its global development, continuation of thermal reactor use and the need for fast breeder reactor (FBR) deployment, availability of uranium resources, establishment of an international framework for non-proliferation and nuclear fuel supply, and the market development for small and medium size reactors, for high temperature reactors and some others.

This study considers three scenarios for capacity growth with different target installed capacities by the end of the twenty-first century: LOW — 2500 GW(e), MODERATE — 5000 GW(e) and HIGH — 10 000 GW(e).

The LOW growth rate scenario is consistent with nuclear energy maintaining its current (as of 2007) share of electricity generation (about 14% of global electricity supply). The MODERATE growth scenario is consistent with nuclear energy increasing its share of electricity generation by displacing other energy sources such as fossil fuels, while the HIGH growth scenario is consistent with nuclear energy being used on a large scale for both electricity generation and non-electric applications such as the production of chemical fuel for transportation purposes and heat for industrial processes.

One of the objectives of the current study is to illustrate, for a range of possible nuclear energy demand scenarios, how nuclear material might flow between different regions of the world. For the purpose of this study, the world has been divided into different regions to allow a global view consistent with that obtained by aggregating regional views. Regions are defined on the basis of geographical proximity, so the specific attributes of countries in a region need to be considered to arrive at the attributes of that region.

Since the study examines possible evolutions of the global nuclear energy system, the starting point is the current mix of reactors. For the future, many different combinations of thermal and fast reactor types could be considered, including evolutionary thermal reactors; high conversion thermal reactors, e.g. reactors operating on the Th-232/U-233 fuel cycle; various small and medium sized thermal and fast reactors, e.g. high temperature reactors; and a variety of fast reactor types with different breeding ratios and using U-238/Th-232 as fertile material and U-235/Pu/ U-233 as fissile material.

The present study, has chosen a set of reactor types that represents those listed above except that, rather than considering the deployment of high conversion thermal reactors, the study takes a low breeding ratio fast reactor and fast reactors that start their operation using fissile plutonium recovered from the spent fuel of thermal reactors or from other fast reactors. Therefore, the study examines how a mixed set of reactors might evolve if the consumption of natural uranium in the twenty-first century were constrained to a value of 20 million Mg, while recognizing that additional resources may well become available.

This provides an insight into the complex interaction between energy demand, possible system evolution, and uranium availability. Restricting uranium consumption to 20 million Mg is not considered a limit on the ultimate availability of uranium since experience has shown that resource estimates can change dramatically when price increases lead to additional exploration and the cost of extracting uranium from unconventional sources can be expected to become more economically viable.

The use of thorium provides a number of opportunities compared with a uranium once-through fuel cycle or a uranium-plutonium closed fuel cycle, e.g. no enrichment needed, fewer minor actinides in spent fuel, higher conversion rate of fertile into fissile material, higher safety margins in fuel rod design, and higher proliferation resistance features. Within the next decades, market conditions may change and technology development will progress to the point that the thorium fuel cycle option could become commercially attractive, so the use of thorium as a fertile material is taken into account in the study.

The evolution of the global nuclear energy system for the three energy demand scenarios was developed using a material flow analysis DESAE code (Dynamics of Energy System of Atomic Energy), recognizing that the penetration of nuclear technology depends on the existing state of regional and national nuclear energy development. The global picture combines regional data which reflects a plausible regional distribution of nuclear energy consumption based on extrapolations that took the current technological basis and the geographical and climate conditions of different regions into account.

As an alternative to deploying fast reactors with high breeding ratios, one could consider the use of thermonuclear fusion systems for breeding Pu/U-233 fuel for use in fission reactors. While such a development is, at present, conceptual, computer analysis can be used to demonstrate the impact of deploying a hybrid fusion-fission system, where the fusion reactor would be used primarily for the production of neutrons rather than conversion of energy per se and so its design and operation would not be determined by energy efficiency requirements but, instead, by its capability to generate fresh fuel (breed fissile material) for use in fission reactors.

The deployment of reprocessing facilities and a combination of thermal and fast reactors in the chosen regions has been demonstrated to be a sufficient condition to achieve the vision of a more equitable distribution of nuclear energy use and hence wealth, consistent with the concept of sustainable development. The establishment of such facilities would be fostered by the development of an appropriate international framework to address such issues as proliferation resistance, physical protection, and security of fuel supply, leading to political acceptance at the national level. If multinational fuel cycle centres were established under appropriate international organization, proliferation resistance, globally, could be enhanced.

The study provides examples of scenarios of transition from the current nuclear energy system based largely on a once-through fuel cycle with thermal reactors to a global nuclear energy system based on a closed fuel cycle with fast reactors. Other transition scenarios could be constructed using different combinations of reactors and fuel cycles.

In the low growth scenario, a global nuclear power capacity increase from 370 GW(e) in 2009 to 2500 GW(e) by the end of the century was chosen. Assuming a free transfer of fuel services between regions, thermal reactors are shown to be sufficient to satisfy demand until 2100 while not exceeding the postulated limit of natural uranium consumption (20 million Mg). The establishment of the necessary spent nuclear fuel disposal facilities for such a nuclear energy system may, however, be problematic.

In the moderate and high growth scenario global nuclear power capacity was assumed to reach 5000 GW(e) and 10 000 GW(e), respectively, by the end of the century. The study demonstrates that closing the fuel cycle and deploying fast reactors in combination with the continued deployment of thermal reactors could accommodate a large expansion of the role of nuclear power while keeping the uranium consumption within the limit of 20 million Mg. Thus, the study has shown that reasonably priced fissile material is not a limiting factor for the sustainability of nuclear power. Further, the study illustrates how all regions in the world could benefit from the deployment of such systems in an equitable manner.

While technical problems could be solved with subsequent investment and R&D efforts within the given time, non-technical challenges could present a serious barrier to the rapid growth of nuclear power and may require appropriate international efforts.

Given the long lead times required to develop and bring new nuclear energy facilities into commercial operation and the costs involved, it is clear that substantial investment by governments will be required. In seeking to justify such investment, a common understanding of the need for innovative nuclear energy systems and of the evolution/transition of nuclear energy systems as innovative technologies are introduced needs to be developed.

1. INTRODUCTION

1.1. BACKGROUND

Access to an affordable and stable supply of energy has been fundamental for the development of modern societies and this will also be the case in the future. Population growth and economic development are the main drivers for increased energy demand. According to recent scenarios [1–9] global primary energy consumption is expected to increase by a factor 1.5–3 by 2050 compared with today, and by 2–5 times by 2100 [1, 2]. The relative growth in electricity demand will be twice as large. In addition to affordability, stability and security of supply, power must also be produced in an environmentally sustainable manner and, in particular, the concern for global warming and climate change has positioned the supply of energy in an environmentally sustainable manner as a key issue of global importance.

The key objective of the INPRO project, as defined in the INPRO Report [10], is to show that nuclear energy is available to contribute in fulfilling energy needs in the twenty-first century in a sustainable manner.

In the 1960s, as nuclear power plants entered commercial operation for the production of electricity, it was envisioned that fast breeder reactors and thermal reactors operating on a Th/U-233 cycle would be needed sooner rather than later as the known resources of uranium were depleted and as the use of nuclear power plants expanded around the world. Proponents of nuclear power have recognized for over 50 years that, with the use of fast breeder reactors (FBR) operating on a closed fuel cycle, fission reactors can make a major contribution to meeting global energy demand essentially indefinitely [11]. But, as the expansion rate of nuclear energy decreased and exploration identified large new reserves of uranium, the apparent need for such advanced systems was pushed into the future and their development slowed, so that the vast majority of nuclear power plants operating today utilize thermal reactors and only a few prototype fast reactors are in operation. Therefore, it appears, today that the wide scale deployment of fast breeder reactors will not occur for at least a few decades. None-the-less, the long term availability of uranium resources at a ‘reasonable’ cost may ultimately constrain the expansion of nuclear power without the use of fast breeder reactors. So, recognizing the strategic importance of nuclear power as a sustainable energy source, a number of countries, all of which are partners in INPRO, continue to pursue the development of fast reactors with a closed fuel cycle and associated reprocessing facilities and technologies recognizing that, in due course, such innovative nuclear energy systems will be needed.

It is also recognized that the deployment of fast reactors and closed fuel cycles will likely take place over several decades, during which changing combinations of fast and thermal reactors will be used for electricity production and possibly other applications such as hydrogen production, water desalination, etc.

1.2. OBJECTIVES

Within this context it was decided that it would be worthwhile to carry out a study under the auspices of INPRO with the following objectives:

(1) Illustrate, using idealized examples, the potential contribution that innovative nuclear energy systems employing fast reactors and closed fuel cycles can make in meeting the global and regional demand for nuclear energy, for a range of possible demand scenarios and, in parallel, also illustrate the potential roles of different reactor types operating in combination in an evolving and growing global nuclear energy system;
(2) Illustrate, for a range of possible demand scenarios, how nuclear materials might flow among different regions of the world in the twenty-first century;
(3) Identify some of the issues that might need to be addressed to implement the global vision of nuclear energy development presented in the study, and, in particular, the vision for the two higher demand scenarios.

The INPRO methodology sets out criteria in seven areas — economics, infrastructure, safety, waste management, proliferation resistance, physical protection, and environment — that need to be satisfied for nuclear energy to be sustainable. It is assumed that the nuclear energy systems discussed in this report will be developed to meet these criteria. The study then illustrates how fast reactors and closed fuel cycles can limit the demand on uranium resources. A number of other assumptions have been made to facilitate the study. These are discussed in more detail in Section 2 and are summarized here:

(1) There will be a continued need for nuclear energy in the twenty-first century and its contribution to total energy supply may increase substantially.
(2) Nuclear energy systems will be used in all regions of the world.
(3) The per capita use of energy will increase dramatically in developing countries, so that by the end of the century the differences in energy intensity among regions are expected to be much smaller, resulting in a more balanced standard of living, in accordance with the concept of ‘sustainable development’.
(4) Thermal reactors will continue to be deployed for many decades to come.
(5) Fast breeder reactors will continue to be developed and will be deployed in significant numbers in due course to satisfy the demand for nuclear power while, at the same time, limiting the demand for uranium, and so ensure that shortages of low to moderate cost uranium resources do not limit the potential of nuclear power. In parallel, the use of reprocessing to close the fuel cycle for both thermal and fast reactors will increase.
(6) The resources of natural uranium available at a reasonable price until the end of the century amount to at least 20 million tonnes but could be significantly greater.
(7) Countries will co-operate to establish regional (maybe multinational) fuel cycle centres which will supply services to countries within a given region and to other regions, fostering an exchange of fresh and spent fuel among regions. The establishment of such facilities is assumed to be supported by an appropriate international framework that addresses issues such as proliferation resistance, physical protection, and security of fuel supply leading to political acceptance at the national level.
(8) The regions receive natural uranium for enrichment, spent fuel for reprocessing, thorium and depleted uranium and produce and supply a range of fuels for use in thermal and fast reactors in all regions. There is neither inter-regional nor intra-regional transport of enriched uranium nor of separated fissile isotopes (Pu, U-233, U-235).
(9) A market for small and medium sized reactors, and for high temperature gas reactors will develop in the course of the century.
(10) The study considers only a limited set of possible innovative nuclear energy systems that might be developed during the twenty-first century.

(11) The deployment of nuclear power in the regions chosen for the study is based on a combination of the currently known status and anticipated growth of nuclear power in all the countries in a given region.

1.3. OUTLINE

Section 2 of this report describes the three different global nuclear energy demand scenarios, the regional groupings of countries, and characteristics of generic reactor types used in the study. It also discusses uranium resources and the choice of a uranium consumption constraint of about 20 million Mg.

Section 3 presents and discusses illustrative examples of evolving regional nuclear energy systems that would satisfy the nuclear energy demand for each of the three assumed global demand scenarios, while constraining the total global consumption of natural uranium to a fixed value of 20 million Mg.

Section 4 considers the inter-regional transfers of nuclear materials associated with the nuclear energy systems posited in Section 3.

Sections 5 and 6 present conclusions and recommendations for future work.

This study is neither a forecast of regional nor of global nuclear power development. Rather, it presents an integrated view of a few potential nuclear energy development pathways that might be followed as nuclear energy is utilized to contribute to meeting the global demand for energy in the twenty-first century.

2. BASIC ASSUMPTIONS USED IN THE STUDY

This section describes the basic assumptions being made within this study.

2.1. GLOBAL NUCLEAR ENERGY DEMAND SCENARIOS

Population growth and economic development are the main drivers that lead to increased energy consumption and so it is clear that energy demand will continue to increase for many decades to come as emerging and developing countries strive for improved standards of health and greater prosperity.

In various reports that examine future global energy demand and supply scenarios [1–9], the expected growth of global primary energy consumption varies over a wide range as shown in Fig. 1 (for more details see Annex I).

Similarly, the expected global growth of nuclear energy also covers a wide range. Fig. 2, taken from Ref. [10], presents results from the Special Report On Emission Scenarios (SRES) developed by IIASA for the IPCC.

Reference [10] also examined the potential global market for nuclear energy for a given SRES energy scenario, the A1T scenario, assuming that further improvements in the economics of nuclear generated power will enable it to gain additional market shares from its competitors (see Fig. 3).

In Fig. 3 the yellow, light blue and grey area represents the forecast of global contribution of nuclear power to energy services (electricity, hydrogen, and heat) as originally assumed in the A1T scenario.Nuclear electricity is the yellow area on the bottom, nuclear hydrogen is the light blue area above that, and nuclear heat (other than for desalination), is the thin sliver of light grey above that. Together, these values correspond to the total nuclear energy production for the A1T scenario and show a rise and fall in nuclear production with a peak around 2070–2080. The stagnation of nuclear growth around 2070 and the following decline is based on the IPCC assumption that renewables, especially solar power will become cheaper than nuclear power at this time.

The orange area in Fig. 3 is additional nuclear generated electricity based on the assumption that improvements in the economics of nuclear electricity generation enable it to win market share from its competitors, mainly from solar power. The large dark blue area is additional nuclear generated hydrogen based on the parallel assumption that improvements in nuclear hydrogen generation are good enough for nuclear energy to win a share of the solar hydrogen market. The contributions of the additional nuclear generated district heat market and nuclear

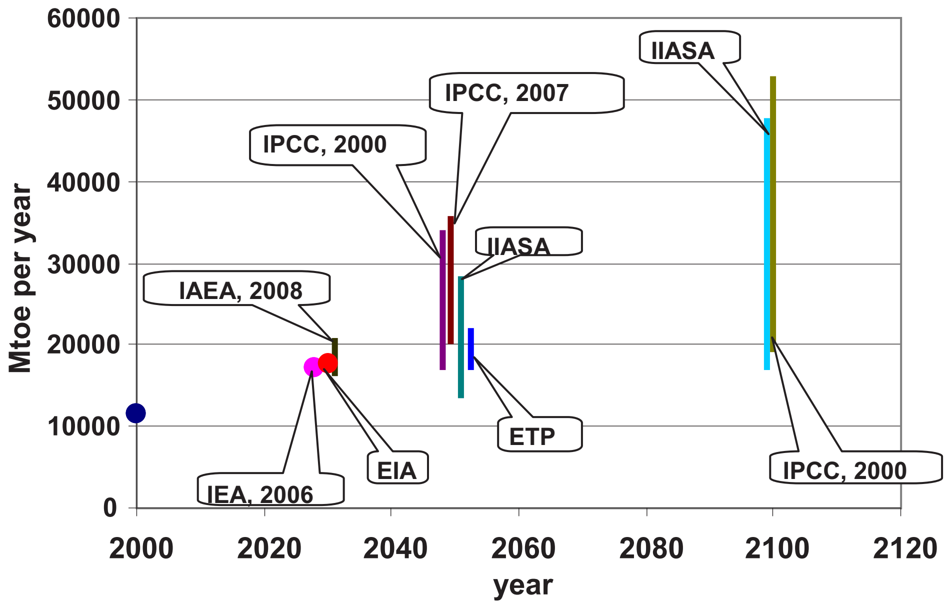

FIG. 1. Scenarios of global primary energy consumption in the twenty-first century (IPCC = International Panel of Climate Change, UN; IIASA = International Institute for Applied Systems Analysis; EIA = Energy Information Agency, DOE; ETP = Energy Technology Perspective, OECD).

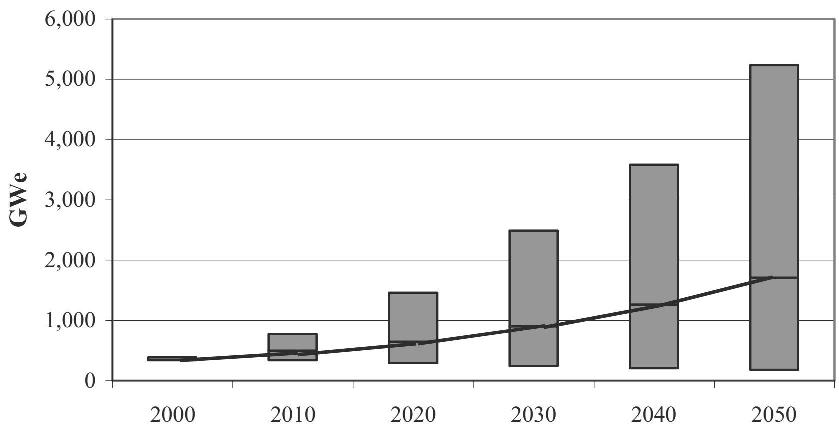

FIG. 2. Range of expected nuclear power capacity in SRES scenarios, 2000–2050. (Solid line represents median) [10].

desalination are too small in the A1T scenario to show up in Fig. 3. The red strip on top is the potential market for nuclear heat for upgrading unconventional oil resources, for coal gasification and liquefaction, and for synthetic fuel production from coal.

2.2. SCENARIOS SELECTED

Given the wide range of possible future demand for nuclear power, it was decided for the present study to consider three nuclear energy scenarios representing low, moderate, and high growth rates of installed nuclear capacity, as summarized in Table 1 and Fig. 4. The three growth scenarios are quite similar until 2030 but then diverge at an increasing rate, particularly after 2050.

The LOW growth scenario is consistent with nuclear energy maintaining its current (as of 2007) share of electricity generation (about 14% of global electricity supply). The MODERATE growth scenario is consistent with nuclear energy increasing its share of electricity generation, by displacing other energy sources such as fossil fuels, while the HIGH growth scenario is consistent with nuclear energy being used on a large scale for both electricity

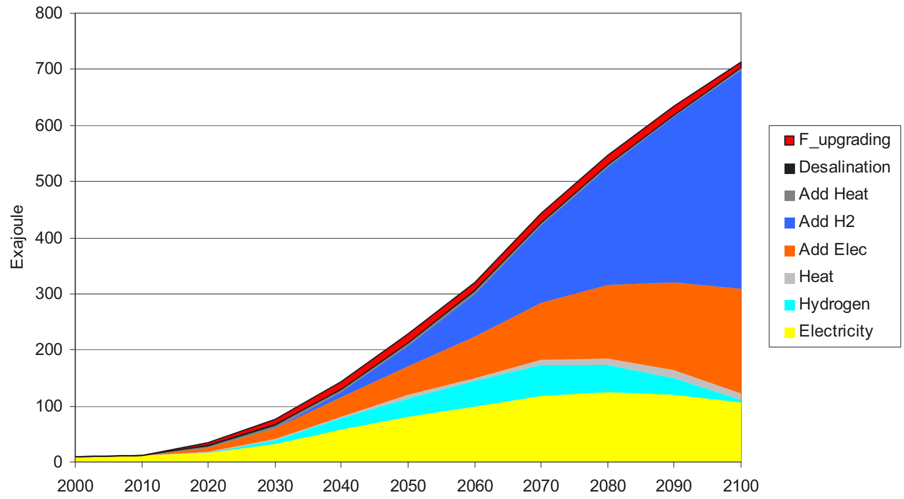

FIG. 3. Potential global market for nuclear electricity, hydrogen, heat, desalination and fossil fuel upgrading for the A1T scenario.

TABLE 1. GLOBAL INSTALLED NUCLEAR CAPACITY AS A FUNCTION OF TIME USED IN THE PRESENT STUDY

	Installed capacity (GW(e))	Installed capacity (GW(e))	Installed capacity (GW(e))
Year	Low growth	Moderate growth	High growth
2009	370	370	370
2030	500	600	700
2050	1000	1500	2000
2100	2500	5000	10000

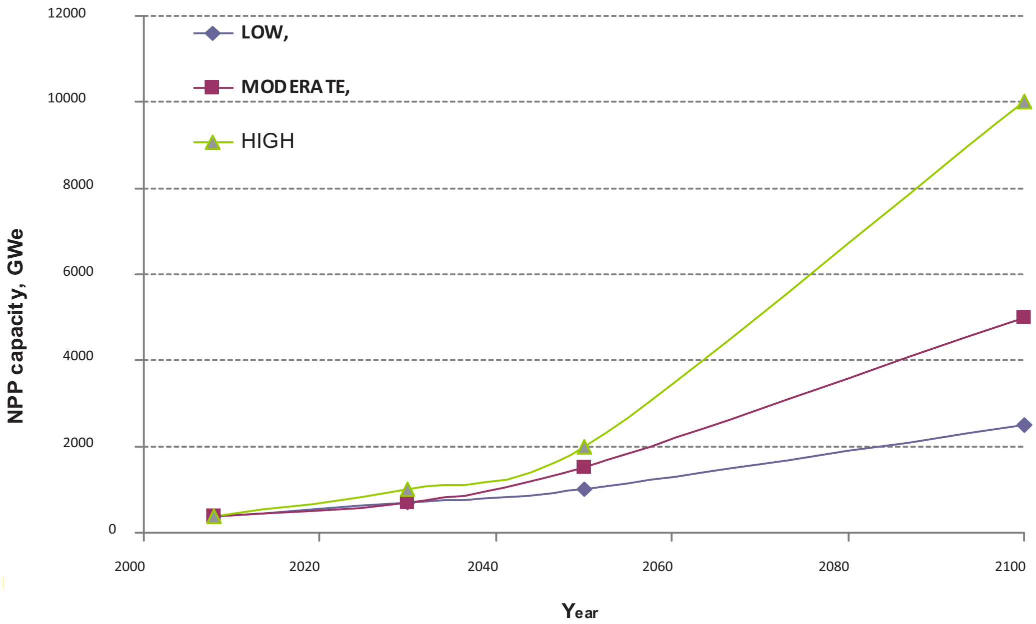

FIG. 4. World nuclear energy scenarios used in the current study.

generation and non-electric applications, such as the production of artificial motor fuels and heat for industrial processes, and is more or less consistent with the potential growth of nuclear power depicted in Fig. 3.

Assuming a load factor of 0.85 and a thermal efficiency of 37%, the corresponding primary energy supplied (see Annex III) would be 1800, 2700 and 3600 Mtoe in 2050 and 4400, 8900 and 18 000 Mtoe in 2100 respectively for the LOW, MODERATE, and HIGH growth nuclear scenarios. These numbers can be compared with the mid-range global energy consumption of the scenarios shown in Fig. 1 of about 25 000 Mtoe in 2050 and about 35 000 Mtoe in 2100. Thus, for example, for the HIGH growth scenario, nuclear power would supply about 15% of the mid-range global primary energy demand by 2050 and about 50% by 2100.

The global energy mix that will actually be used at a given point in time will be determined by many factors, including:

- The availability of technologies at the time of potential deployment, which in turn will depend on prior decisions taken concerning investing in their development;
- Relative costs of alternatives, their environmental impact, and security of supply;
- Societal and political acceptance, both at the time of deployment and also at the time when decisions are taken to invest in their development.

A view of future global energy mix must also take into account the attributes of the different energy systems. An important feature of nuclear energy is that it provides a very stable base load energy supply and therefore complements the non-hydro renewable energies, whose main drawback is their intermittency. Nuclear energy is the only non-CO_2 emitting electricity generation technology already deployed on a large scale today and which can be expanded significantly.

2.3. REGIONAL BREAKDOWN

As noted in Section 1, one of the objectives of the current study is to illustrate, for a range of possible nuclear energy demand scenarios, how nuclear materials might flow among different regions of the world. For the purpose of this study, the world has been divided into different regions so that a global view can be obtained that is consistent with that obtained by aggregating regional views.

There are many approaches that might be used to define regions. For example, one approach is to utilize the current and short term extrapolations of national nuclear capabilities as a differentiating attribute. With such an approach one might distinguish among technology developing/holder countries, countries having nuclear power experience but which are not technology developers and those countries which currently do not have nuclear power experience.

This approach has been used in the INPRO collaborative project GAINS [13]. With such an approach, other subdivisions are of course possible. For example, countries might be grouped as follows:

- Countries with well established nuclear energy systems and with well developed domestic nuclear technology capabilities, and with plans for moderate expansion of their nuclear power programmes, including for example France and Japan;
- Countries with rapidly growing economies and ambitious plans for nuclear energy expansion programmes, for example China and India;
- Countries with modest nuclear energy expansion programmes which already have a small number of nuclear power plants;
- Newcomer countries that are starting a nuclear energy programme or are seriously assessing the nuclear energy option.

Another approach is to use the definition of regions based on geographic proximity. In this case, the specific attributes of countries belonging to a specific geographic region need to be considered to arrive at the attributes of that region. Since, in this study, material transfer among geographic regions is of interest, this approach has been adopted.

The regions chosen generally follow the approach taken by the IAEA [6] and are shown in Fig. 5. The countries that belong to each region are set out in Table III–2 of Annex II.

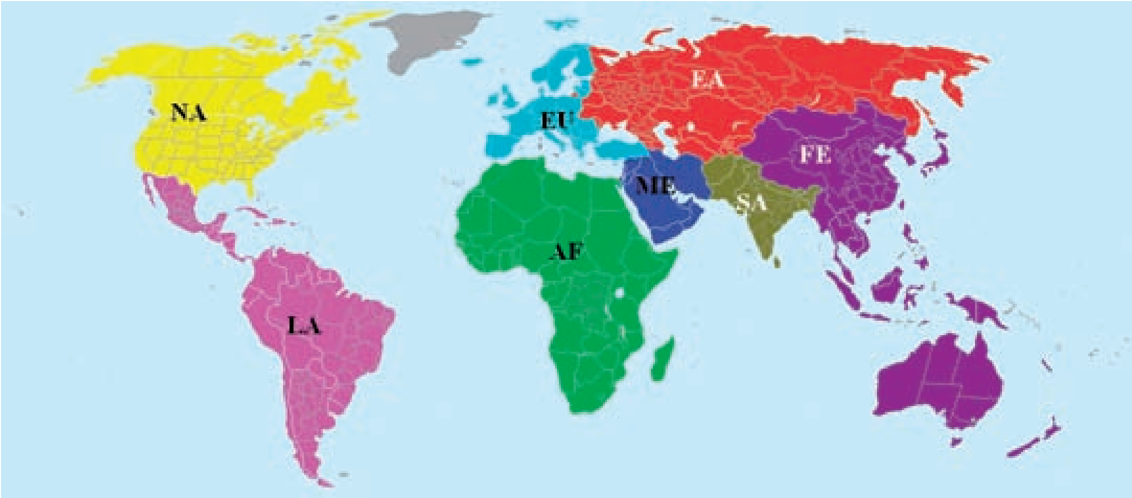

Fig. 5. Geographic regions used in the study (NA = North America, LA = Latin America, AF = Africa, ME = Middle East, EU = Europe, FE = Far East, SA = South Asia).

The country-specific data related to growth of energy demand (anticipated growth of population, industry, etc.) of all countries within a region has been, in general, taken from the database of the Food and Agriculture Organization of the United Nations (FAO) [17].

The regional nuclear power profiles, as of 2007, including the data for the number and types of installed reactors and fuel cycle facilities, and anticipated growth of nuclear power, have been determined by summing up the country specific data for all countries comprising a particular region.

The largest share of nuclear power growth in coming years is expected to take place in countries with rapidly growing economies, notably China and India. Considering the well articulated position of these countries to achieve rapid future growth of nuclear in the near to mid term, the most recent projections for the growth of nuclear energy in these two countries were taken into consideration in this study (See Annex IX for details).

2.4. PROPERTIES OF GENERIC REACTOR TYPES USED IN THE STUDY

Since the study examines possible evolutions of the global nuclear energy system the starting point is the current fleet of reactors. As of 2007, about 97% of nuclear installed capacity consists of water cooled reactors of various types with somewhat different characteristics. Pressurized heavy water moderated and cooled reactors (PHWR), for example, provide for on-power fuelling and, in the original variants, permit use of natural uranium as a fuel. Out of the total fleet of current generation reactors, light water cooled and moderated reactors (LWR) account for the largest share, comprising about 88%, of the world's installed capacity.

While it is recognized that even among the LWRs there are several variants — each with its own fuel cycle attributes — taking into account differences among the current fleet of water cooled reactors would add considerable complexity to this study without adding much value. So, for the purpose of this study, all water cooled reactor types are represented by a notional reactor type 'WCR' (water cooled reactor), whose fuel cycle characteristics are similar to current generation LWRs.

Looking to the future evolution of the global reactor fleet, many different combinations of thermal and fast reactor types could be considered, including for example evolutionary thermal reactors, high conversion thermal reactors (e.g. reactors operating on the Th-232/U-233 fuel cycle), various small and medium sized thermal and fast reactors (e.g. including high temperature reactors), and a variety of fast reactor types with different breeding ratios and using U-238 and/or Th-232 as fertile material (see also Annex VIII and Annex IV).

In performing the present study, a set of reactor types has been chosen that are more or less representative of the reactor types listed above, except that rather than considering the deployment of high conversion thermal reactors, the study utilized a low breeding ratio fast reactor and, in this study, all fast reactors start their operation using fissile plutonium recovered from the spent fuel of thermal reactors or from other fast reactors.

The thermal reactor options comprise evolutionary water reactors as well as small and medium sized reactors, assuming that a market for such reactors will develop in due course for the selected representative types presented in Table 2

The fast reactor variants are presented in Table 3. The basic parameters of the selected thermal and fast reactor types are set out in Tables 4 and 5..

TABLE 2. TYPES OF THERMAL REACTORS CONSIDERED IN THE STUDY

Reactor type	Characteristics of thermal reactors
WCR	Corresponds to present day LWR as concerns its fuel cycle parameters and thermodynamic efficiency.
WCR-M	Represents a modernized LWR with higher fuel burnup and higher thermodynamic cycle efficiency.
SMR	A small PWR having a somewhat higher specific consumption of natural U[a] compared with LWR; which could turn out to be better adapted to specific regional conditions.
HTR	A high temperature reactor operating on uranium fuel. This reactor type could be used for high temperature heat applications in various technological processes, including the production of hydrogen or motor fuels. These nuclear energy applications have not been considered in detail in this study and the energy produced is expressed in terms of its electrical equivalent.
HTR (U3)	A high temperature reactor similar to the HTR, but using Th as a fertile and U-233 as fissile material. In this study its deployment in the nuclear energy system assumes the simultaneous availability of U-233 breeders (see fast reactor types in Table 3).

[a] It should be noted that not all PWR-type SMRs have higher specific consumption of natural uranium compared with a LWR, see, for example, Refs [17, 18]. Moreover, several of the designs of SMRs being developed have fast neutron spectrum.

TABLE 3. TYPES OF FAST REACTORS CONSIDERED IN THE STUDY

Reactor type	Characteristics of fast reactors
FBR-C	A liquid metal cooled fast reactor design with a breeding ratio close to one. Like all other fast reactors in this study, it would be initially fuelled with uranium and Pu from the spent fuel of thermal reactors, and subsequently would shift to operating on its own Pu, consuming only depleted uranium. The low breeding ratio would limit its capacity growth rate.
FBR-S	An advanced sodium cooled fast reactor design featuring a higher core power density (about twice above that of thermal reactors) and Pu breeding in both the core and in reactor blankets. The overall breeding ratio is 1.4.
FBR-A	A fast reactor with fuel breeding ratio of 1.6. This concept is characterized by direct loading of fuel elements containing depleted U instead of NU into the core, and a bigger blanket leading to a higher Pu breeding ratio.
FBR-A (Th)	A fast reactor similar to FBR-A, but containing Th-232 in the radial blanket, where the breeding of U-233 takes place. This reactor is considered in the HIGH scenario, which foresees also the presence of high temperature reactors operating in the thorium fuel cycle.

TABLE 4. BASIC REACTOR DESIGN PARAMETERS OF THERMAL NEUTRON REACTORS

Parameter	WCR	WCR-M	SMR	HTR	HTR (U3)
Capacity, GW(e)	1	1.5	0.25	0.3	0.3
Efficiency	0.33	0.35	0.33	0.45	0.45
Heavy nuclei load, t	80	135	20	6	6
U-235 enrichment, %	4	4.9	4	8	—
U-233 enrichment, %	—	—	—	—	8
Burnup, GW·day/t	45	60	40	80	100
Share of fissile isotopes in SNF, %	1.4	1.4	1.4	3.4	2.6
SNF cooling and reprocessing time, years	5	5	5	5	5
Natural U consumption (U-235 content in tails 0.15%), tU_{nat}/ GW(e)·year	180	150	210	140	—

TABLE 5. BASIC REACTOR DESIGN PARAMETERS OF FAST NEUTRON REACTORS

Parameter		FBR-C	FBR-S	FBR-A	FBR-A (Th)
Capacity, GW(e)		1.2	0.9	1.8	1.8
Efficiency		0.43	0.43	0.43	0.43
Heavy nuclei load, t	core	64	23	23	23
	axial blanket		19	60	60
	radial blanket		31	37	37
Enrichment by Pu fission, %		9.5	12	25	25
Breeding ratio		1.05	1.4	1.6	1.6
Burnup, GW·day/t		65	85	140	140
Excess Pu fission production, kg/GW(e)·year		40	270	295	195
Excess U-233 production, kg/GW(e)·year		—			100
SNF cooling and reprocessing time, years	core	1	3	3	3
	blanket	—	1	1	1

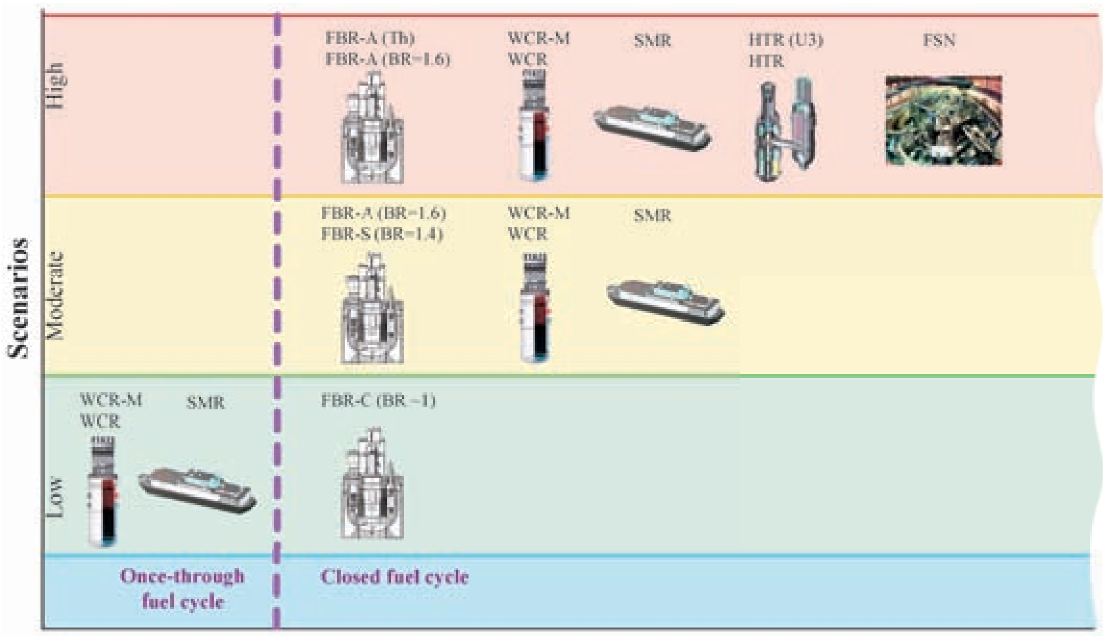

FIG. 6. World nuclear energy systems consisting of different reactor types for scenarios defined in the study (low, moderate, high). (LWR ≡ WCR).

Reactor design parameters presented above for WCR correspond to the average parameters of LWRs used today, but reflect current trends of their modernization and fuel cycle improvement. Regarding high temperature reactors and fast breeders with different breeding parameters, various design options — mostly dating back to the middle and end of the 1970s — have been reviewed to select the basic representative design parameters for these reactor types.

The combinations of reactor types used for the three selected energy demand scenarios (Table 1 and Fig. 4) are shown in Fig. 6.

Today, most reactors operate on an open (once through) fuel cycle and this is expected to continue for many years. But as fast reactors are introduced on a commercial scale, some thermal reactors may shift to a closed fuel cycle, the number increasing with time as the demand for Pu to start up fast reactors increases. The division between the closed and once through cycles is shown in Fig. 6. The figure shows that for the moderate and high growth scenarios, no thermal reactors are operating on the once through cycle, which indicates this change in the deployment strategy, but does not exclude the continued use of thermal reactors with the once through cycle for some time in these scenarios.

2.5. AVAILABLE URANIUM AND THORIUM RESOURCES

Uranium resources

According to the 'red book' of the OECD/NEA and IAEA [14], the total amount of identified uranium resources (previously called 'known conventional resources') available at an extraction cost below 130 US $/kg U is currently estimated to be 5 million Mg. The total amount of undiscovered resources (prognosticated and speculative) available at an extraction cost below US $130/kg U, which are expected to be discovered soon either at known deposits or nearby, together with more speculative resources, which are assumed to exist in geologically favourable — but still unexplored — areas, including the resources with unknown extraction cost, is estimated to be 10.5 million Mg. Thus the currently known world uranium resources with the highest extraction cost considered acceptable today (below US $130/kg U), as well as additional resources based on conformity trends and parameters, theoretical resources estimated by geological extrapolation, as well as speculative amount to about 16.0 million Mg.

The regional distribution of conventional (identified and undiscovered) uranium resources in accordance with the grouping of countries assumed is given in Annex III (Table III–1).

Unconventional uranium resources (from which uranium is extracted as a by-product only) extend the resource base even further. Additionally, very few countries declare the amounts of their unconventional resources. The last estimate of uranium potentially recoverable from phosphates, non-ferrous metal ores, carbonates, slates and lignites lies between 7 and 22 million Mg. It is expected that with time the technologies used for extracting uranium from such sources will evolve and the cost of uranium from such sources will decrease.

One of the objectives of the present study is to illustrate how fast breeder reactors can be deployed, in due course, to contribute to meeting the global demand for nuclear power while, at the same time, limiting the demand for uranium and so ensure that shortages of low to moderate cost uranium resources do not limit the use of fission reactors. Based on the discussion above, one can be reasonably confident in using a resource estimate of 20 million Mg of uranium as fissile feedstock, available at a reasonable cost, for a growing and evolving nuclear energy system in the twenty-first century. Therefore for this study we examine how a mixed and evolving fleet of reactors might evolve, if the consumption of natural uranium in the twenty-first century were constrained to a value of 20 million Mg, while recognizing that additional resources may well become available.[1] Doing so provides an insight into the complex interaction between energy demand, possible system evolution with time, and uranium availability. Restricting uranium consumption to 20 million Mg is not be considered to represent a limit on the ultimate availability of uranium, since experience has shown that resource estimates can and have changed dramatically when price increases lead to additional exploration [15], and, as noted above, the cost of extracting uranium from unconventional sources can be expected to become more commercially attractive.

Thorium resources

Uranium resources can be augmented by thorium (Th-232), which is three to four times more abundant in nature than uranium although unlike uranium the data on thorium deposits in the world are not well documented yet. Th-232 is a fertile material which can be converted in a thermal or fast breeder reactor to the fissile material U-233.

Utilisation of thorium provides a number of opportunities compared to uranium once-through fuel cycle and/or uranium–plutonium closed fuel cycle, e.g. no enrichment is needed, less production of minor actinides in SNF, higher conversion rate of fertile into fissile material, higher safety margins in fuel rod design, and higher proliferation resistance features.

One should also mention significant challenges that exist along with the opportunities of a thorium fuel cycle, e.g. the need to apply remote control for handling of SNF and for fuel fabrication due to the high gamma radiation level, and to develop the infrastructure for a commercial thorium fuel cycle.

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[1] Since uranium represents only a few per cent of the cost of energy from nuclear power plants operating today, a large increase in uranium prices could be tolerated without changing the basic economics of such plants. However, absence of U from markets would obviously result in delays in capacity commissioning.

However, within the next decades market conditions may change and technology development will progress to the point that the thorium fuel cycle option could become commercially attractive. For this reason the use of thorium as a fertile material is taken into account in the present study.

Additional information on the use of thorium is presented in Annexes VIII and X.

2.6. MODELLING APPROACH

The evolution of the global nuclear energy system for the three energy demand scenarios (Fig. 4) was developed using a material flow analysis DESAE code (Dynamics of Energy System of Atomic Energy) (see Ref. [16] and Annex VI). The global picture was obtained by combining regional data which took into account a plausible regional distribution of nuclear energy consumption. The latter was based on extrapolations that took into account the current technological basis of different regions, geographic and climate conditions, recognizing that the penetration of nuclear technology would depend on the existing state of nuclear energy development in different regions and countries within a given region, as will become clear when looking at the results presented in Section 3. The aim was not to predict the future development of nuclear power region by region, but to identify issues that might affect such development.

Exchange of nuclear material between regions

It has been assumed that fuel resources, i.e. fresh and spent nuclear fuel, can be freely exchanged among regions, and that enriched uranium and other fissile material from reprocessing would not be transferred from one region to another. These materials would rather be used for the production of fresh fuel that, like natural uranium and thorium, also could be transferred. The assessment of possible inter-regional flows of nuclear fuel cycle materials is a major output from this study.

With these assumptions, regional fuel cycle centres need to be established to make fuel materials management economically profitable and limit at the same time concerns about proliferation and physical protection.

Potential role of regional fuel cycle centres

International/multinational fuel cycle centres may service different regions and different countries within a given region. Such fuel cycle centres would provide a range of services, including enrichment and spent fuel reprocessing, as well as the supply of fuel for use in thermal and fast reactors.

The wastes that arise from reprocessing might be disposed in regional waste management facilities or might be returned to the region/country of origin, as is done today. This issue was not addressed in the current study.

In the absence of such multinational fuel cycle centres, a growing nuclear energy system with fast reactors and a closed fuel cycle would require the development of many national facilities to serve domestic needs. These facilities would be smaller than regional ones and due to the economics of scale associated with larger multinational regional facilities, would increase the demand and cost for safeguards and physical protection.

Development of nuclear energy in the regions

Projections of the per capita nuclear electricity generation have been made for different regions using the UN data on the projected population of these regions [17], such that by the end of this century the per capita nuclear energy consumption is more equitably distributed among regions, consistent with the concept of sustainable development. At intermediate times the per capita share in different regions will vary from that at the start of the century and that assumed at the end of the century. These differences are based on a judgment of the levels of technological preparedness of the different regions for large scale nuclear energy deployment, with account taken of the time needed to establish a nuclear power programme. It is clear that the resulting regional distributions cannot be considered to be a comprehensive forecast, since, for example, they do not fully take into account development of other energy technologies, as well as demographic and environmental conditions in the different regions. However, they represent a possible and plausible evolution of the regional distribution of installed nuclear energy capacity, normalized to the global capacity assumed for the different nuclear energy demand scenarios.

Development of global nuclear energy scenarios

All three global scenarios evaluated in this study, i.e. the LOW, MODERATE and HIGH growth scenario, were based on the assumption that the amount of natural uranium to be consumed by the end of the century should not exceed 20 million Mg (see Section 2.5).

The nuclear energy system structure under the MODERATE and HIGH growth scenarios assumes that nuclear energy deployment on these larger scales is fostered by introduction of fast reactors beginning around 2030. It should be noted that a delay in the introduction of fast reactors would require deployment of additional thermal reactor capacities to satisfy the predicted demand for energy, but in such a situation it would not be possible to limit the consumption of uranium to the end of the century to 20 million Mg. Thermal reactors deployed in the time frame of the 2030–2040s could be expected to operate to the end of the century or longer.

Development of regional nuclear energy systems

For the nuclear energy systems in the three scenarios that employ several reactor types, determining an appropriate regional distribution of capacities for each reactor type presents an intricate task.

This study assumed that the capacities should be distributed among the regions to satisfy the following constraints:

— Total capacity of each type of reactor should be equal to nuclear capacity identified at the global level (see Fig. 7, for instance);
— Total capacity of all reactor types in a region should be equal to the installed capacity of all nuclear power plants in this region (see Tables 7, 9).

Calculations of installed capacities of different reactor types in regions should take account of the fact that the capacities of reactors launched earlier would be largely responsible for the capacity range and structure of regional capacities to be installed in the years to come. Many reactor designs have an operational lifetime of 60 years and being launched in 2010, for instance, they will operate until ~2070. This could limit the possibilities to change the future regional capacity structure. More importantly, this will affect the regional distribution of fast reactors to be introduced after 2030. By that time, some regions, e.g. North America (NA) and Europe (EU) would already have large thermal capacities in operation, and therefore these regions would not be able to accommodate many fast reactors because total regional nuclear structures and capacities are assumed to be fixed. In order to ensure the global fuel equilibrium and the sufficient production of plutonium, fast reactors would have to be deployed in other regions, some of which are currently considered to be less prepared for fast reactor development.

On the other hand, one cannot arbitrarily distribute capacities for different reactor types by regions. Thus, to arrive at an internally consistent picture of regional distributions of reactor types for different demand scenarios it was necessary to resort to a trial and error approach and the use of engineering judgment.

Interregional transfer of nuclear material

The amounts of interregional transfers of different fuel cycle products were determined using DESAE-TRANSPORT code (see Annex VII), which allows interregional supplies to be calculated against given resource production and consumption scopes in a region, as well as a matrix of interregional exchange priorities for this resource, such that total regional consumption plus regional exports equal total production.

While some countries may establish domestic fuel supply capabilities, by 2030 it is assumed that their contribution to global supply will be limited. For the purposes of interregional fuel exchange simulation, it was assumed that by 2030 the regional distribution of fuel cycle enterprises, and in particular reprocessing facilities, will not be significantly different from the current one. However, by the end of the century each region is assumed to develop all facilities for a complete nuclear fuel cycle, which includes for example installing a regional (and maybe a multinational) fuel cycle centre, thus levelling the distribution of these capabilities among the regions.

Interregional fuel exchanges were calculated and balanced so that the demand in each region was met completely (in particular, with account taken of work carried out by facilities in other regions). Two stages of inter-regional exchanges were considered.

- After natural U was mined in one region, it is transported for enrichment to another region, which produces fuel from it and sends it to yet another region.
- Closed fuel cycle enterprises were analyzed on a similar basis. Spent nuclear fuel (SNF) is delivered to the region, which has capacities for its reprocessing. This region also fabricates new fuel assemblies, which then are sent to other regions on demand.

3. NUCLEAR CAPACITY SCENARIOS

This section presents the results for the three global scenarios chosen in the current study illustrating the growth of installed nuclear capacity on a regional basis and the share of the global installed capacity for each reactor type as defined in Tables 2 and 3.

3.1. NUCLEAR POWER CAPACITY IN THE LOW GROWTH SCENARIO

Table 1 and Fig. 4 present the expected global increase in nuclear power capacity for the three scenarios chosen.

Figure 7 and Table 7 illustrate the expected regional distribution of nuclear power installations for the LOW growth scenario.

As can be seen from Table 7 for the LOW growth scenario, the increase in the demand for nuclear energy in North America (NA) and Europe (EU) by 2100, compared with the supply in 2007, is relatively modest, factors of 3 and 2, respectively. The growth ratios in Eurasia (EA) and the Far East (FE) are roughly a factor of 10 higher and the greatest growth, expressed as a ratio with respect to the installed capacity in 2007, is in Latin America (LA), Middle East (ME), South Asia (SA), and Africa (AF), respectively, pointing to an assumed global equalization of demand and wealth.

In this LOW growth scenario the installed nuclear capacity at the end of the century in South Asia (SA), and the Far East (FE) exceed that in North America (NA) and Europe (EU), while that of Africa (AF) and Eurasia (EA) are about the same as for North America (NA). While the installed capacity in Latin America (LA) grows by a

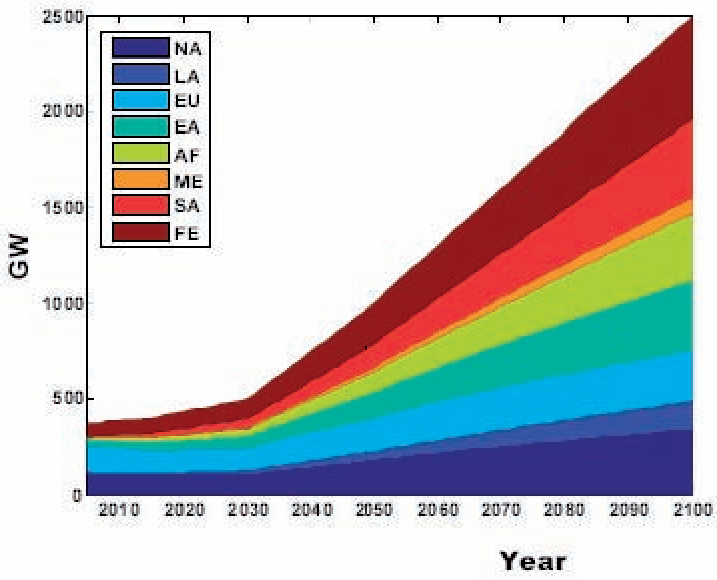

FIG. 7. Installed nuclear power capacity by regions in the LOW growth scenario (GW(e)) (NA = North America, LA = Latin America, EU = European Union, EA = Eurasia, AF = Africa, ME = Middle East, SA = South Asia, FE = Far East).

TABLE 7. INSTALLED NUCLEAR CAPACITY IN THE LOW GROWTH SCENARIO AS A FUNCTION OF TIME FOR THE DIFFERENT REGIONS (GW(e))

Year	NA	LA	EU	EA	AF	ME	SA	FE	Total
2007	113.2	4.1	134.7	35.2	1.8	1*	4.2	78.4	371.64
2030	107	19	115	62	38	9	46	105	500
2050	179	47	174	134	105	25	123	212	1000
2100	341	149	264	365	350	86	409	537	2500
Ratio**	3	36	2	10	194	86	97	7	7

* The value for 2007 for ME is based on the planned capacity to be installed by about 2010.
** Ratio is the value of installed capacity in 2100 divided by the value of 2007.

TABLE 8. SPECIFIC NUCLEAR POWER PRODUCTION IN THE YEAR 2100 BY REGIONS IN THE LOW GROWTH ENERGY DEMAND SCENARIO (kw·h/CAPITA)

Year	NA	LA	EU	EA	AF	ME	SA	FE	Average
2100	4004	1355	3048	7887	898	1236	971	1670	1635

TABLE 9. ASSUMED DEVELOPMENT OF STRUCTURE OF REACTOR FLEET BY REGIONS IN THE LOW GROWTH ENERGY DEMAND SCENARIO (GW(e)) INSTALLED

Year	Reactor	NA	LA	EU	EA	AF	ME	SA	FE
2007	Various	113.2	4.1	134.7	35.2	1.8	1*	4.2	78.4
2030	WCR & WCR-M	107	19	115	62	38	9	46	105
2050	WCR & WCR-M	179	47	174	134	105	25	123	212
2100	WCR-M	331	99	254	345	255	56	349	487
	SMR	10	50	10	20	95	30	60	50
2007	Total	341	149	264	365	350	86	971	537

* The value for 2007 for ME is based on the planned capacity to be installed by about 2015.

factor of 36 the total capacity is less, by 2100, than in Africa (AF), reflecting in part differences in population, but also the fact that Latin America (LA) has much larger hydro resources to be developed compared with Africa (AF).

Table 8 presents the specific power production by nuclear energy in the different regions at the end of the century. Table 8 shows that by 2100 in Eurasia (EA) the highest contribution of nuclear power per capita will be reached, followed by North America (NA) and Europe (EU). As stated above, the lower specific values of other regions are partly due to differences in population and availability of other energy sources such as fossil fuels and hydro power.

The assumed distribution of nuclear energy capacities, i.e. the assumed structure of the reactor fleet for the LOW energy demand scenario is shown in Table 9. Total capacity for each region was set in accordance with Table 7, with subsequent calculation of fuel consumption, spent fuel production, etc.

Note that it is assumed that a market for SMR develops and that by 2100 in the LOW energy demand scenario about 300 GW(e) of capacity is represented by these reactors. The distribution of SMRs among the regions in this study is based on an engineering judgement, taking into account considerations such as geography and grid size.

Figure 8 shows the assumed global nuclear energy system structure for this LOW growth scenario. In total, for this scenario, the total power produced in the period 2010 to 2100 by nuclear is about 0.8 million TW·h, i.e. about 2800 EJ.

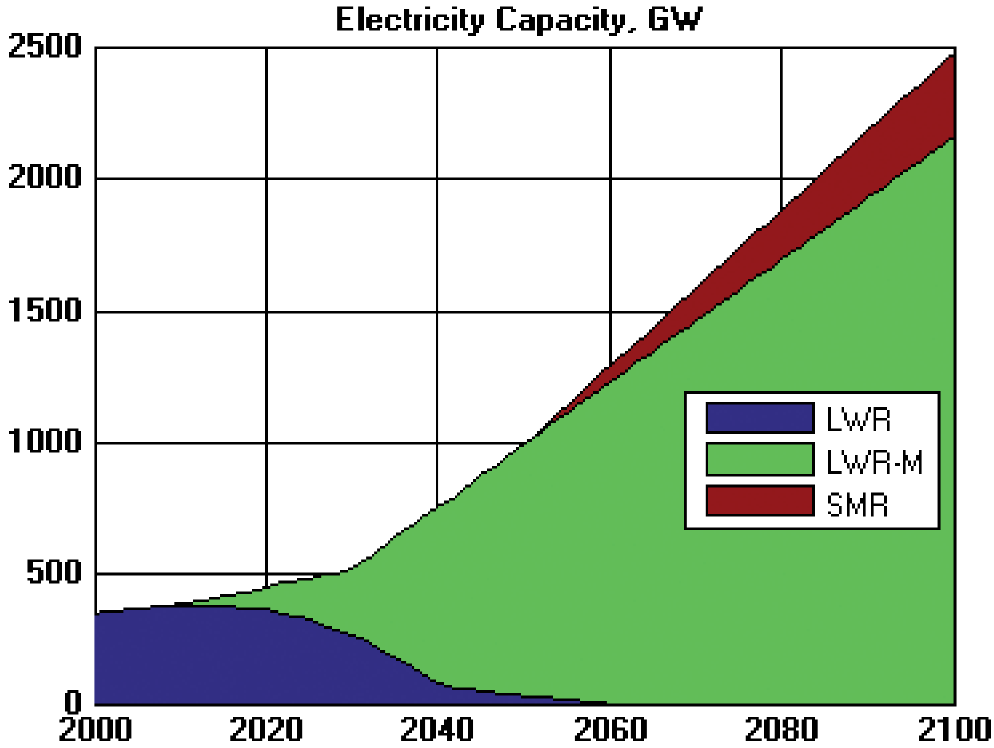

FIG. 8. Assumed global nuclear energy installed capacity by reactor type, as a function of time, for the LOW growth scenario, considering only deployment of thermal reactors.

Annual requirements of natural uranium production in Mg per year and separated work units are shown in Fig. 9.

By the end of the century, the accumulated consumption of natural U would reach 18.5 million Mg, including 17 million Mg consumed in large reactors, and about 1.5 million consumed in small and medium reactors. SMR installed capacity would, by then, reach about 13% of cumulative nuclear power plant capacities and their number would have a significantly higher share due to their smaller unit size.

Thus, for the LOW scenario, deployment of the closed nuclear fuel cycle technologies is not needed to limit the consumption of uranium resources to the assumed reserve of 20 million Mg of natural uranium by the end of the century.

The number of separated work units and the mass of natural uranium, in Mg (tons), in this scenario, differ by almost exactly a factor of 1000 and so in Fig. 9 the plots of these parameters overlap. Since this scenario considers only a once-through fuel cycle, there is no fuel reprocessing and neither uranium nor Pu is extracted from SNF for recycling as MOX fuel in WCRs. If uranium from spent fuel were considered under this scenario, the amount of separation work would be practically the same, while the demand for natural uranium would be reduced by about 10%. So, while such recycling might be, and already is, done in some regions, the general picture is not affected to any significant extent.

The greatest infrastructural problems under the LOW growth scenario may be associated with the disposal of the spent nuclear fuel (SNF) assemblies. The total amount of SNF to be disposed will reach about 1.6 million Mg of SNF — containing about 23 000 Mg of Pu at the end of the century. Disposal of this fuel would probably require several tens of repositories. (The capacity of the Yucca Mountain repository, for example, in the USA is limited by legislation to about 70 000 Mg of SNF.) The need for such repositories could lead to increased pressure to establish regional (and multinational) repositories under appropriate international agreements.

While recycling Pu and uranium in WCRs does not impact the general picture, the introduction of fast breeder reactors that utilize Pu recovered from SNF would lead to a significant reduction in the consumption of uranium resources and at the same time to a significant reduction of the volume of SNF for final disposal.

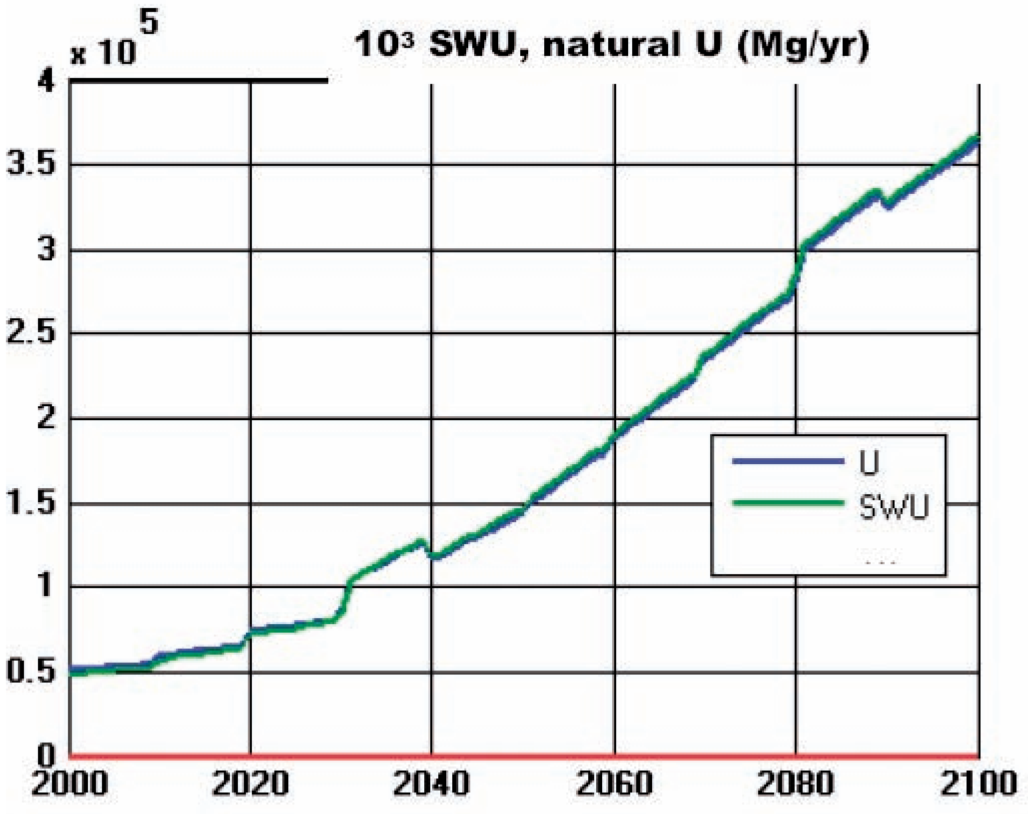

FIG. 9. Annual demand of natural U production and separation work in the LOW growth scenario.

Introduction of fast reactors into the LOW growth scenario

The impact of introducing fast reactors, with a low breeding ratio of 1.05, beginning in 2030 was studied (see Fig. 10) for the LOW growth scenario.

This option would lead to a substantial reduction in the consumption of natural uranium to an accumulated value of ~10 million Mg by 2100 (compare Fig. 9 with Fig. 11).

The reduction in the demand for uranium could be accompanied by the use of depleted uranium in the fuel for the fast reactors (see Fig. 12).

3.2. NUCLEAR POWER CAPACITY IN THE MODERATE GROWTH SCENARIO

Figure 13 and Table 10 illustrate the assumed regional distribution of nuclear power installations for the MODERATE growth scenario.

As can be seen by comparing Tables 7 and 10, the increase in demand (defined by the 'Ratio') for the MODERATE growth scenario is ~ factor of 2–3 higher than for the LOW growth scenario in almost all regions. An exception is the Eurasia region (EA) where the growth is approximately the same for both the LOW and MODERATE scenario.[2]

As discussed for Table 10 (together with Table 7) similar tendencies can be observed by comparing Tables 8 and 11, e.g. an increase in specific power production in SA in the MODERATE scenario by a factor of three

[2] The installed capacity reached in 2100 is even reduced from 365 GW(e) in the LOW scenario to 341 GW(e) for the MODERATE scenario. This is caused by the trial and error approach taken and the need to ensure that the sum of regional capacities equals the total installed capacity while also keeping the total uranium consumption below 20 million Mg.

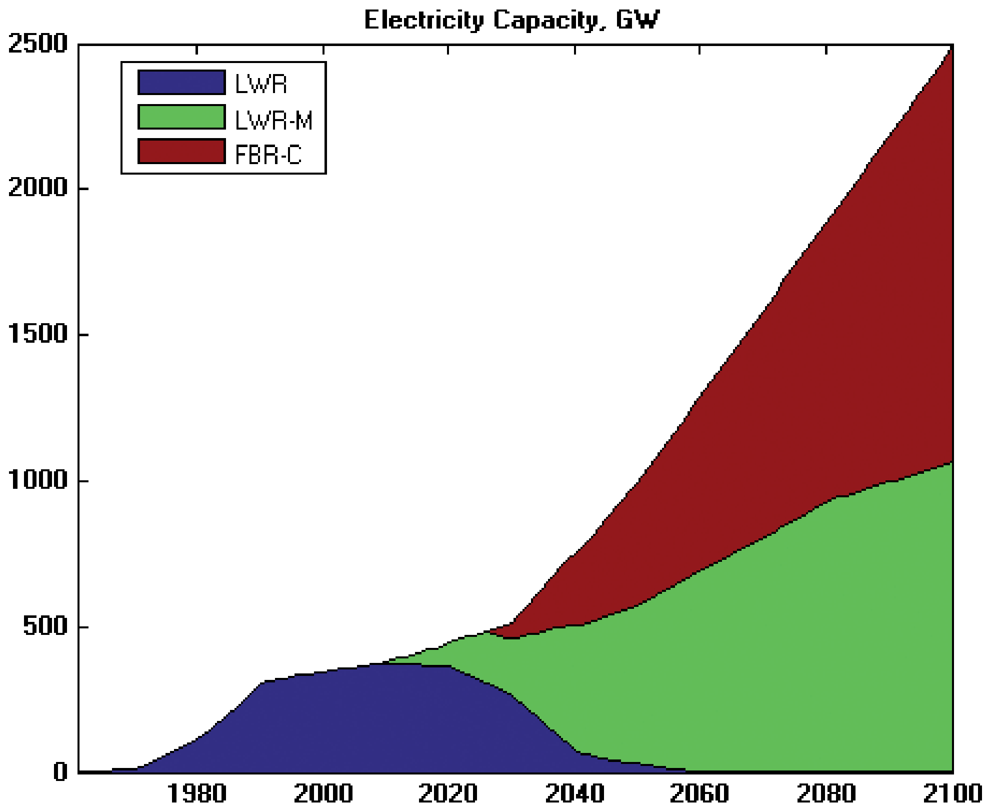

FIG. 10. Global nuclear energy installed capacity by reactor type, as a function of time, for the LOW growth scenario, assuming the deployment of both thermal and fast reactors operating on a closed fuel cycle.

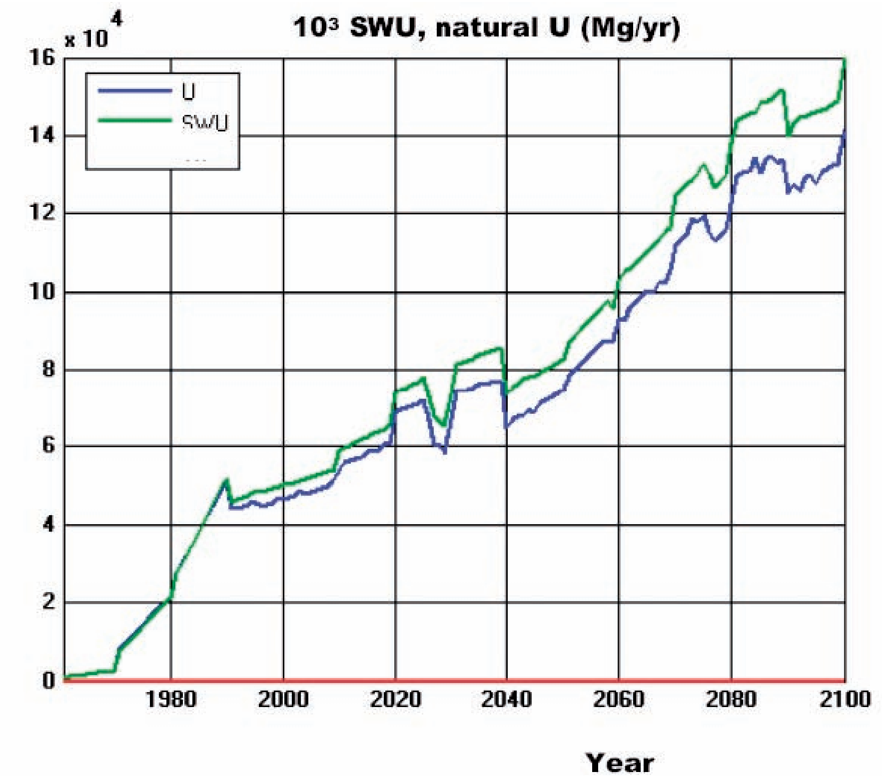

FIG. 11. Annual U production and SWU demand corresponding to the nuclear energy system shown in Fig. 10 (thermal plus fast reactors in LOW growth scenario).

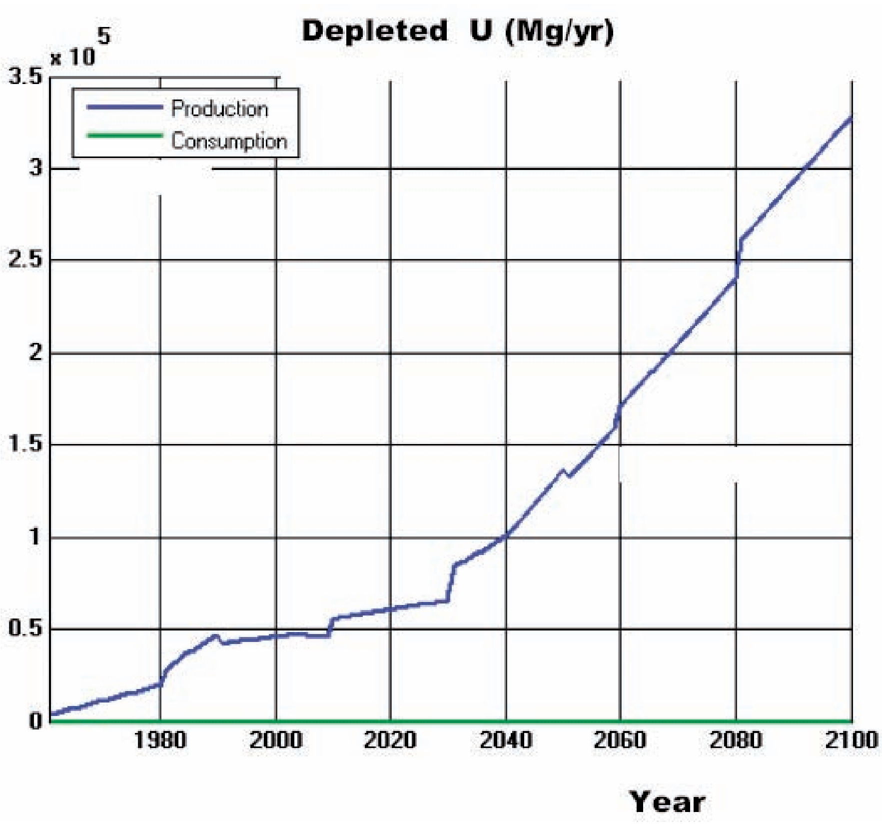

FIG. 12. Amount of depleted uranium produced per year, LOW scenario, corresponding to the nuclear energy system shown in Fig. 10 (thermal plus fast reactors).

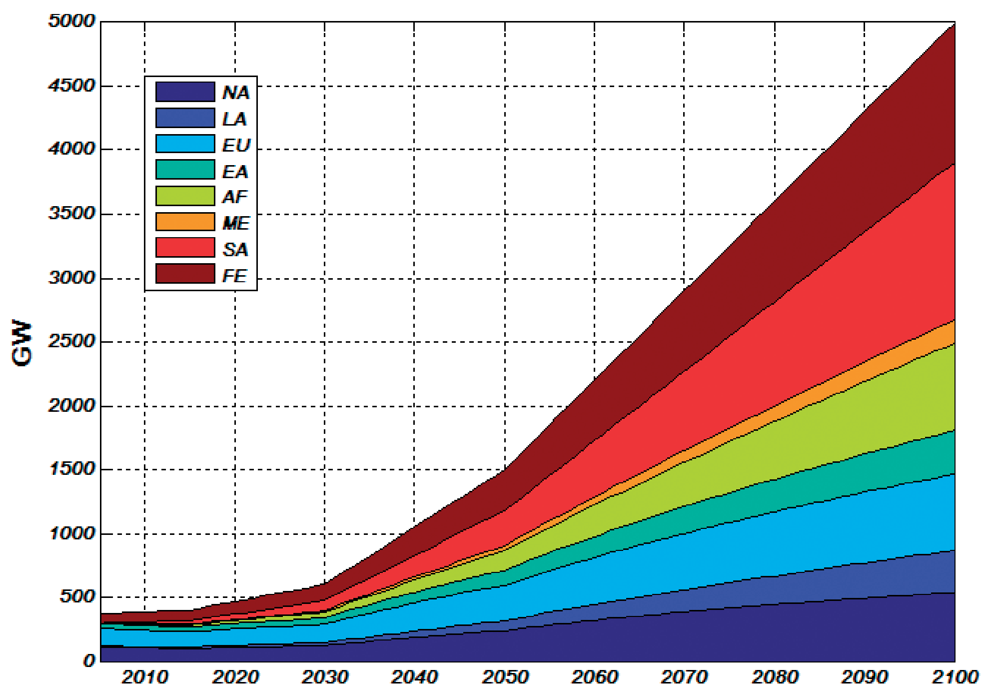

FIG. 13. Installed global nuclear power capacity by regions for the MODERATE growth scenario (GW(e)) (NA = North America, LA = Latin America, EU = European Union, EA = Eurasia, AF = Africa, ME = Middle East, SA = South Asia, FE = Far East).

compared to the LOW growth scenario. The total power produced between 2010 and 2100 in the MODERATE growth scenario is about 4900 EJ, which is about 75% greater than that for the LOW growth scenario.

The calculations showed that for the MODERATE scenario the deployment of fast reactors is needed if the constraint that the total accumulated demand for natural uranium does not exceed 20 million Mg by the end of the century is to be satisfied.

Two situations were considered for this MODERATE growth scenario, both based on deploying an assumed combination of thermal reactors, both large and small, and fast reactors.

In the first case (case 1) two types of fast reactors are deployed, namely type FBR-S with a breeding ratio of 1.4 and FBR-A, with a breeding ratio of 1.6. In the second case (called case 2) only one type of fast reactor is deployed, namely type FBR-S.

In the following, firstly, results for case 1 will be presented and thereafter for case 2.

Case 1 with two types of fast reactors

Figure 14 shows the assumed global energy system structure for case 1 (with two types of fast reactors FBR-S and FBR-B).

Table 12 shows the distribution of thermal and fast reactor types (two types, case 1) for all regions, in addition to the global picture shown in Fig. 14. By 2030, some 49 GW(e) of fast breeder reactors are assumed to be installed, all in South Asia, compared with 551 GW(e) of thermal reactors and by 2050 the fast reactor fleet will have grown to 579 GW(e), 66% of which is in the South Asia and the Far East regions, compared with 921 GW(e) of thermal reactors, of which 112 GW(e) are in the SMR category. By the end of the century, the fast reactor fleet totals some 2422 GW(e), 66% of which is again in South Asia and the Far East regions, compared with 2857 GW(e) of thermal reactors. Thus, globally, the growth rate of fast reactors exceeds that of thermal reactors, especially in South Asia. Achieving such a rapid growth represents a significant challenge.

Case 2 with only one type of fast reactor

Figure 15 shows the assumed global energy system structure for case 2 (with only one type of breeder reactor FBR-S).

TABLE 10. INSTALLED NUCLEAR CAPACITY AS A FUNCTION OF TIME FOR THE DIFFERENT REGIONS FOR THE MODERATE SCENARIO (GW(e))

Year	NA	LA	EU	EA	AF	ME	SA	FE	Total
2007	113.2	4.1	134.7	35.2	1.8	1*	4.2	78.4	371.64
2030	128	24	144	61	44	11	57	130	600
2050	240	77	280	115	152	40	273	322	1500
2100	538	331	595	341	683	184	1231	1097	5000
Ratio	5	81	4	10	379	184	293	14	13

* The value for 2007 for ME is based on the planned capacity to be installed by about 2015.

TABLE 11. SPECIFIC ANNUAL NUCLEAR POWER PRODUCTION IN 2100 BY REGIONS (kW·h/capita)

Year	NA	LA	EU	EA	AF	ME	SA	FE	Average
2100	6315	3009	6880	7381	1754	2642	2924	3415	3270

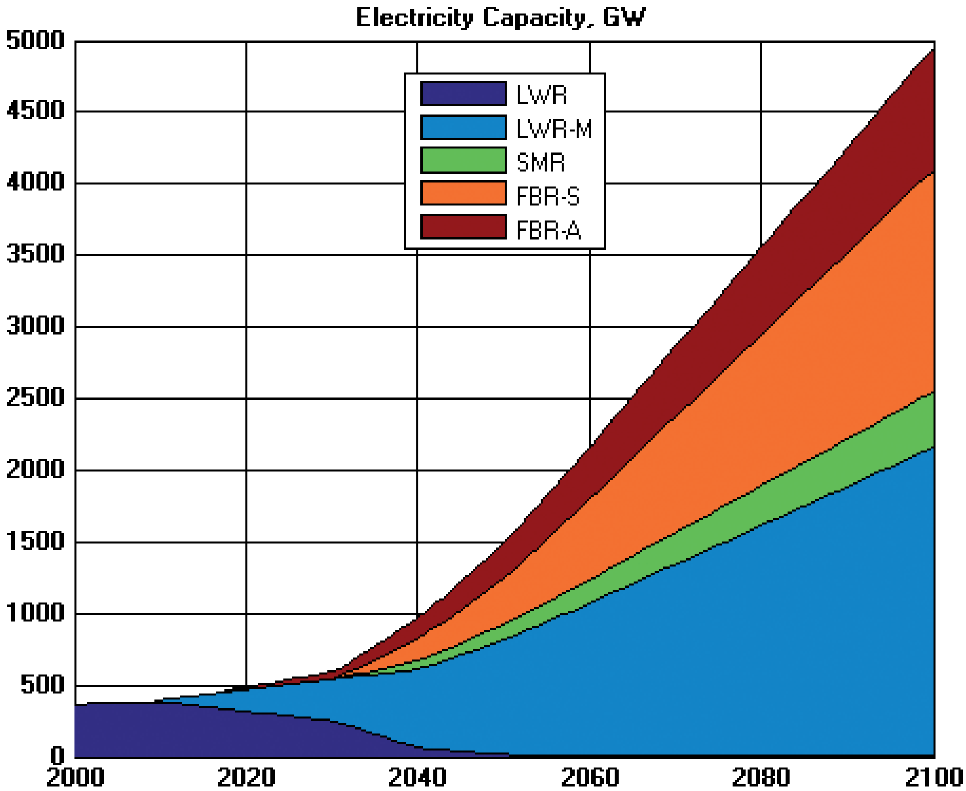

FIG. 14. Global nuclear energy installed capacity by reactor type as a function of time for the MODERATE growth scenario, considering the deployment of two types of fast reactor — case 1.

TABLE 12. ASSUMED STRUCTURE OF REACTOR FLEET (CASE 1) BY REGIONS FOR THE MODERATE SCENARIO CORRESPONDING (GW(e))

Year	Reactor	NA	LA	EU	EA	AF	ME	SA	FE
2007	Various	113.2	4.1	134.7	35.2	1.8	—	4.2	78.4
2030	WCR	60	4	95	26	2	0	2	59
	WCR-M	71	13	79	34	24	6	4	72
	FBR-A	0	0	0	0	0	0	49	0
2050	WCR-M	179	48	201	52	121	28	8	173
	FBR-S	60	9	76	47	0	0	12	124
	FBR-A	0	0	0	0	0	0	251	0
	SMR	3	22	4	14	37	14	0	18
2100	WCR-M	376	136	320	125	503	75	0	631
	FBR-S	154	118	263	186	56	44	348	395
	FBR-A	0	0	0	0	0	0	858	0
	SMR	8	77	12	29	128	65	0	72

For case 2, the accumulated consumption of natural uranium would total 20 million Mg by the end of the century. At that time, thermal reactors would account for about 60% of the installed capacity while fast reactors would account for 40%. Small and medium reactors would represent about 10% of the global capacity. Large scale fuel reprocessing is foreseen to begin at about 2025, reaching ~30000 Mg/year by 2050 and 60000 Mg/year by 2100.

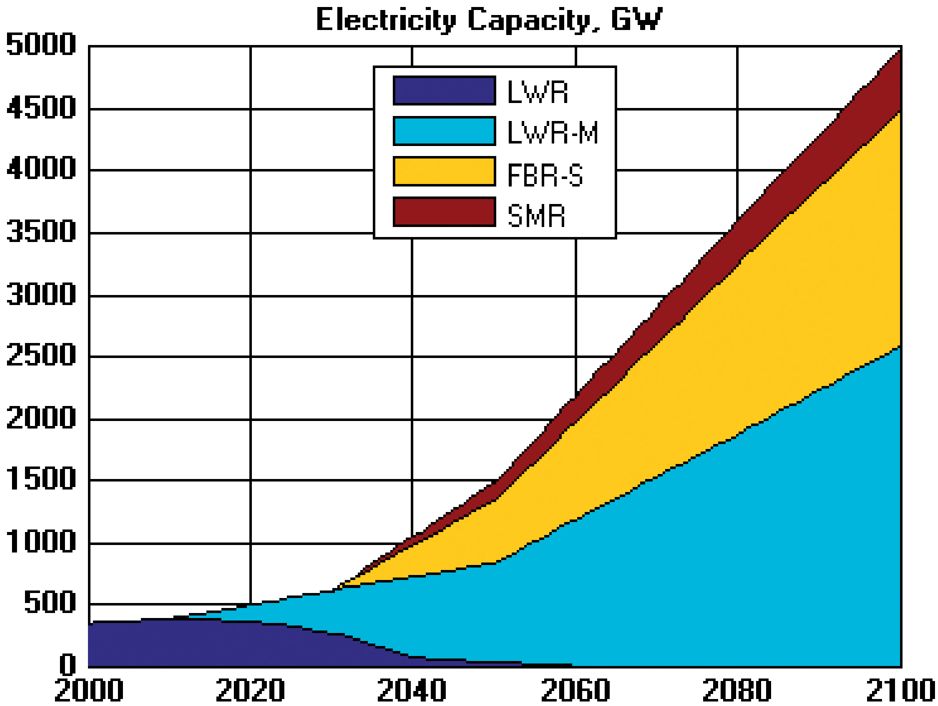

FIG. 15. Global nuclear energy installed capacity (GW(e)) by reactor type, as a function of time, for the MODERATE growth scenario, considering the deployment of only one type of fast reactor — case 2.

Comparison of case 1 and case 2

The annual demand for uranium and enrichment for case 1 and 2 is shown in Figs 16 and 17, respectively. In comparison to case 2, in case 1 as of 2100 the deployment of the fast reactor type FBR-A (with a breeding ratio of 1.6) replaces about 500 GW(e) more of thermal reactor capacity and substitutes about 500 GW(e) more of fast reactor capacity of type FBR-S with a breeding ratio of 1.4. The net result is a reduced demand for natural uranium.

In neither case is the large scale deployment of high temperature reactors (HTR, see Table 2) explicitly considered. High temperature reactors, with a harder neutron spectrum compared to water cooled, reactors are not well suited to using Pu because of their epi-thermal neutron capture resonance and, in any case, all Pu recovered from reprocessing spent fuel from the thermal fleet and the fast reactor fleet is needed as fissile material for the startup of additional new fast reactors in an expanding fleet. None-the-less, a small number of high temperature reactors operating on enriched uranium could well be introduced in the system either for process heat applications or the production of electricity. In such a case their specific fuel consumption parameters would be close to that for a WCR-M and so no practical purpose is served by modeling them as a distinct reactor type.

A number of challenges are expected to arise that would need to be met for the MODERATE growth scenario presented here to be realized. These include the following:

- — The requirement for the large scale reprocessing of spent fuel;
- — Challenges — technical, financial, infrastructural, etc. — of developing and deploying fast reactors of the type and at the rate assumed;
- — Intra-regional and inter-regional transfers of irradiated and fresh fuels;
- — Intra-regional and inter-regional transfers of radioactive waste, possibly including both the high level waste (HLW) and the long lived low and intermediate level waste (L&ILW) from reprocessing;
- — Associated legal, societal, and regulatory considerations.

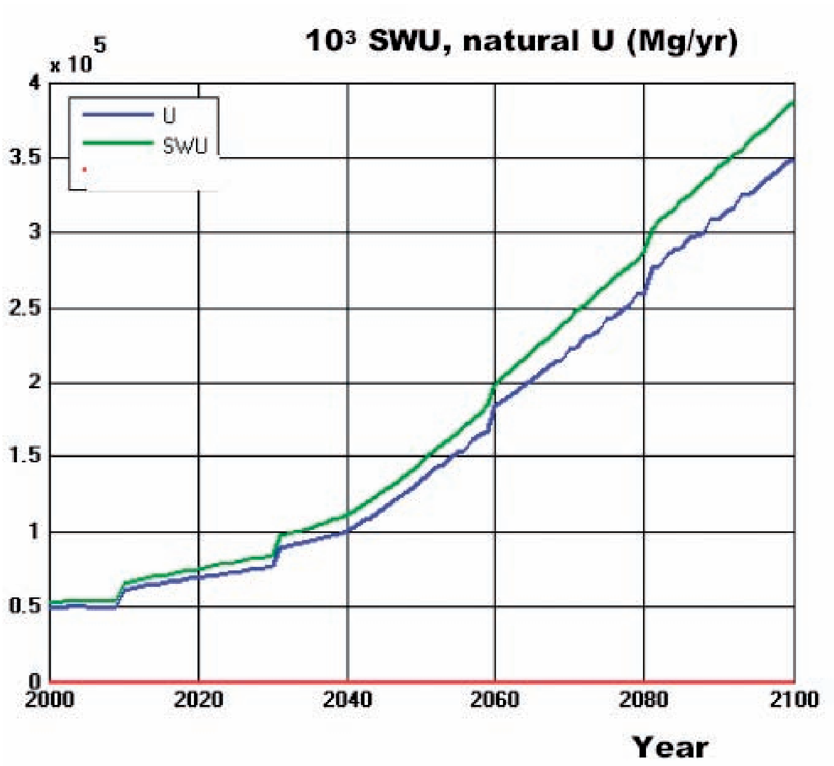

FIG. 16. Annual demand for natural uranium and enrichment for the MODERATE growth scenario — case 1. The accumulated demand for uranium resources totals less than 20 million Mg by 2100.

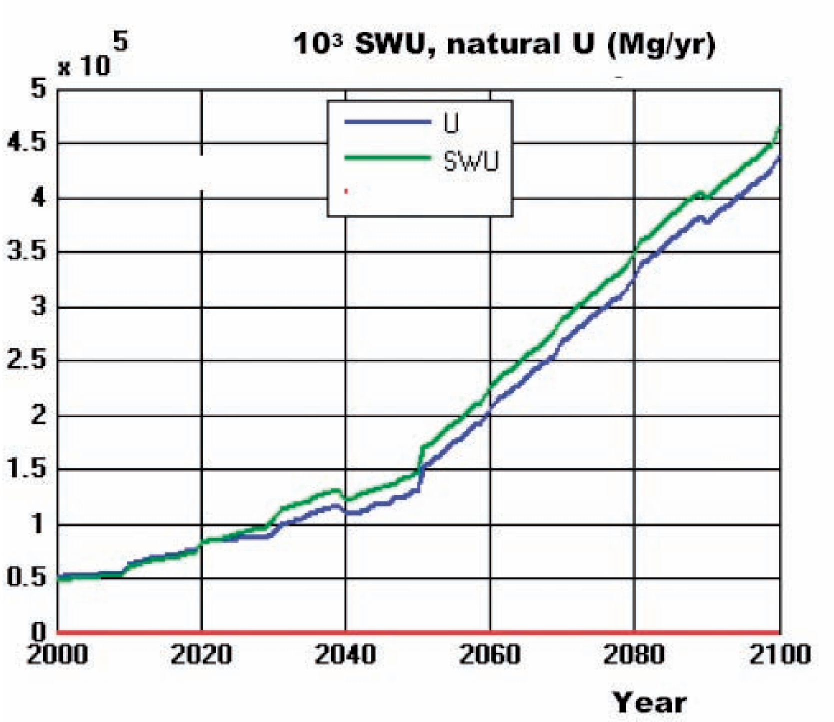

FIG. 17. Annual demand for natural uranium and enrichment for the MODERATE growth scenario — case 2. The accumulated demand for uranium resources totals 20 million Mg by 2100.

Some aspects of inter-regional transfers are discussed in Section 4 of this report. Other reactor combinations and fuel cycles could be considered for the MODERATE scenario, for example, those where fast reactors start with enriched natural uranium (see Annex IV). In this case the requirements to breeding are essentially reduced. Although the corresponding studies have not been performed in much detail, none-the-less the preliminary information presented in Annex IV indicates that, in due course, the current study should be extended to include other such systems.

3.3. NUCLEAR POWER CAPACITY IN THE HIGH GROWTH SCENARIO

Figure 18 and Table 13 illustrate the regional distribution of nuclear power installations for the HIGH growth scenario. From the current vantage point the HIGH growth scenario may be considered to be close to or even beyond the plausible limit of nuclear energy growth in this century

The installed capacity in each region is, for the HIGH growth scenario, about twice of that for the MODERATE growth scenario. The nuclear energy produced in the HIGH growth scenario between 2010 and 2100 is about 8100 EJ, a factor of 2.9 times that for the LOW growth scenario.

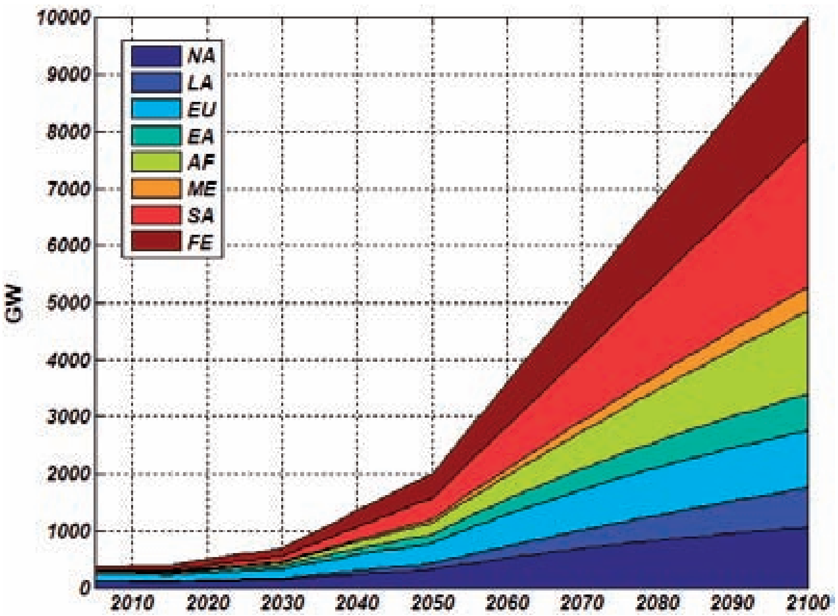

FIG. 18. Installed nuclear power capacity by regions for the HIGH growth scenario, GW(e). (NA = North America, LA = Latin America, EU = European Union, EA = Eurasia, AF = Africa, ME = Middle East, SA = South Asia, FE = Far East).

TABLE 13. INSTALLED NUCLEAR CAPACITY AS A FUNCTION OF TIME FOR THE DIFFERENT REGIONS FOR THE HIGH GROWTH SCENARIO

Year	NA	LA	EU	EA	AF	ME	SA	FE	Total
2007	113.2	4.1	134.7	35.2	1.8	1*	4.2	78.4	371.64
2030	150	29	171	62	48	13	67	161	700
2050	322	108	352	148	211	62	380	418	2000
2100	1058	702	997	639	1449	429	2613	2112	10 000
Ratio	10	170	7	18	800	430	620	27	27

* The value for ME for the year 2007 is based on the planned capacity to be installed by 2015.

Table 14 for the HIGH scenario shows similar trends as Tables 7 and 10 for the LOW and MODERATE scenario, respectively. In 2100 the Eurasian region (EA) will reach the highest annual energy production by nuclear, followed by North America and Europe.

As for the LOW and MODERATE growth scenarios, a nuclear energy system structure was chosen for the HIGH growth scenario so that the accumulated demand for natural uranium did not exceed 20 million Mg by 2100.

The structure of the nuclear energy system, i.e. the reactor fleet, is a logical extension of that proposed for the MODERATE scenario. It includes large thermal reactors (WCR and WCR-M), small and medium thermal reactors (SMR), two types of fast reactors (FBR-A and FBR-A(Th), both with a breeding ratio of 1.6), and thermal high temperature reactors, operating on U-235 (HTR) and on a Th/U-233 fuel cycle (HTR-U3).

Figure 19 illustrates the global nuclear energy system structure for this HIGH growth scenario and Table 15 summarizes the distribution of reactor installations by region. Similar to the MODERATE growth scenario, by 2030 some 56 GW(e) of fast breeder reactors are assumed to be installed, all in South Asia, compared with 644 GW(e) of thermal reactors and by 2050 the fast reactor fleet has to grow to 831 GW(e), 67% of which is in South Asia and the Far East regions, compared with 1150 GW(e) of thermal reactors, of which 254 GW(e) are HTR. By the end of the century, the fast reactor fleet totals some 8170 GW(e), 51% of which is in South Asia and the Far East regions and 17% is in Africa and the Middle East regions, compared with 1828 MW(e) of thermal reactors. Thus, globally, the growth rate of fast reactors will far exceed that of thermal reactors and especially so in South Asia, Far East, Africa and the Middle East. Achieving such a rapid growth represents a significant challenge.

TABLE 14. SPECIFIC ANNUAL ENERGY PRODUCTION BY NUCLEAR POWER PLANTS IN 2100 BY REGIONS (kW·h/CAPITA)

Year	NA	LA	EU	EA	AF	ME	SA	FE	Average
2100	12421	6389	11525	13822	3724	6163	6208	6573	6541

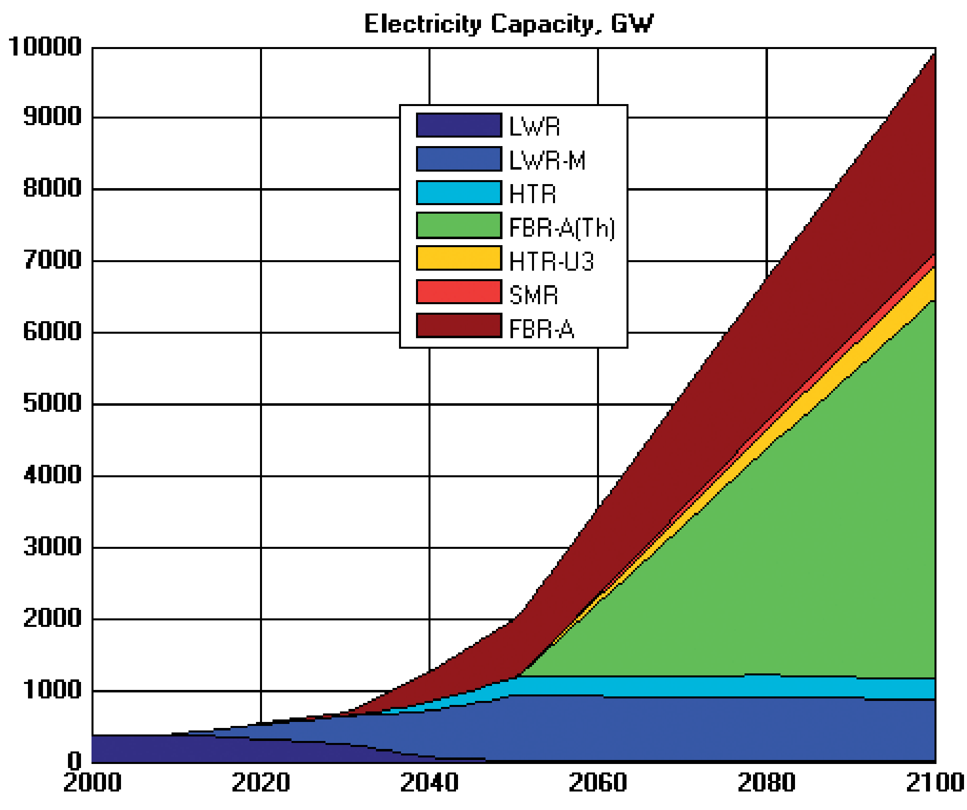

FIG. 19. Assumed global nuclear energy installed capacity by reactor type as a function of time for the HIGH growth scenario.

TABLE 15. CAPACITY STRUCTURE OF REACTOR FLEET BY REGIONS FOR THE HIGH GROWTH SCENARIO CORRESPONDING TO THE GLOBAL PICTURE SHOWN IN FIG. 19

Year	Reactor	NA	LA	EU	EA	AF	ME	SA	FE
2007	Various	113.2	4.1	134.7	35.2	1.8	1*	4.2	78.4
2030	WCR	60	4	95	26	2	0	2	59
	WCR-M	92	18	105	38	30	8	6	99
	FBR-A	0	0	0	0	0	0	56	0
2050	WCR-M	158	85	202	55	201	56	14	145
	FBR-A	120	13	85	59	0	0	324	230
	HTR	44	9	66	34	10	6	43	42
2100	WCR-M	124	74	182	60	195	81	18	144
	FBR-A	209	226	104	185	449	166	881	595
	HTR	23	28	22	37	37	25	74	55
	HTR-U3	53	50	46	55	54	28	97	81
	FBR-A(Th)	645	298	639	295	657	100	1511	1210
	SMR	4	26	4	8	57	29	32	25

* The value for 2007 for ME is based on the planned capacity to be installed by about 2010/2011.

By the end of the century, nuclear installed capacity would consist of:

— Thermal reactors (about 25%; thirty per cent of this amount would be high temperature reactors shaped to produce about 1 Btoe of hydrogen or motor fuels);
— Fast reactors (75%) with high fuel breeding ratio (BR = 1.6).

Fast reactors would generate plutonium to fuel the expanding fleet of fast reactors and also, beginning around 2040, uranium-233 to feed high temperature reactors operating on the thorium fuel cycle, HTR-U3.

Small and medium thermal reactors would provide about 3.5% of nuclear energy capacities. It should be noted that the decrease in the capacity of small and medium reactors, compared with the MODERATE growth scenario, is offset by the development of high temperature reactors, which can also be considered as medium sized reactors. The development of the Th fuel cycle would be determined by the deployment of high temperature reactors, which initially would utilize U-235, beginning in 2030 but which would also utilize U-233 produced in fast reactor blankets beginning about 2050.

Large scale spent nuclear fuel (SNF) reprocessing would have to start by about 2025. SNF reprocessing is estimated to be 40 000 Mg/year by 2050 and 160000 Mg/year by 2100.

Aspects of deployment of the Th fuel cycle in the near and longer terms are discussed briefly in Annex VIII (and more completely in Sections 3.4.2 and 3.5.1 of Ref. [12], full report on CD ROM).

Annual requirements for natural uranium production and enrichment for the HIGH growth scenario are shown in Fig. 20.

In the case of the HIGH growth scenario, the growth rate of the annual demand for uranium (Fig. 20) is tending towards zero at the end of the century, whereas for the LOW and MODERATE growth scenarios the slopes are still positive (see Figs 9 and 16). This difference could be attributed to the introduction of fast reactors with a high breeding ratio and the timely introduction of a Th fuel cycle, and highlights the impact to be obtained from such actions. However, like in the case of the MODERATE scenario, alternative combinations of fast and thermal reactors, specifically for the case when fast reactors are being started from enriched natural uranium, need to be investigated in the future.

As for the MODERATE growth scenario, a number of challenges would need to be met for the HIGH growth scenario to be realized. These include the following:

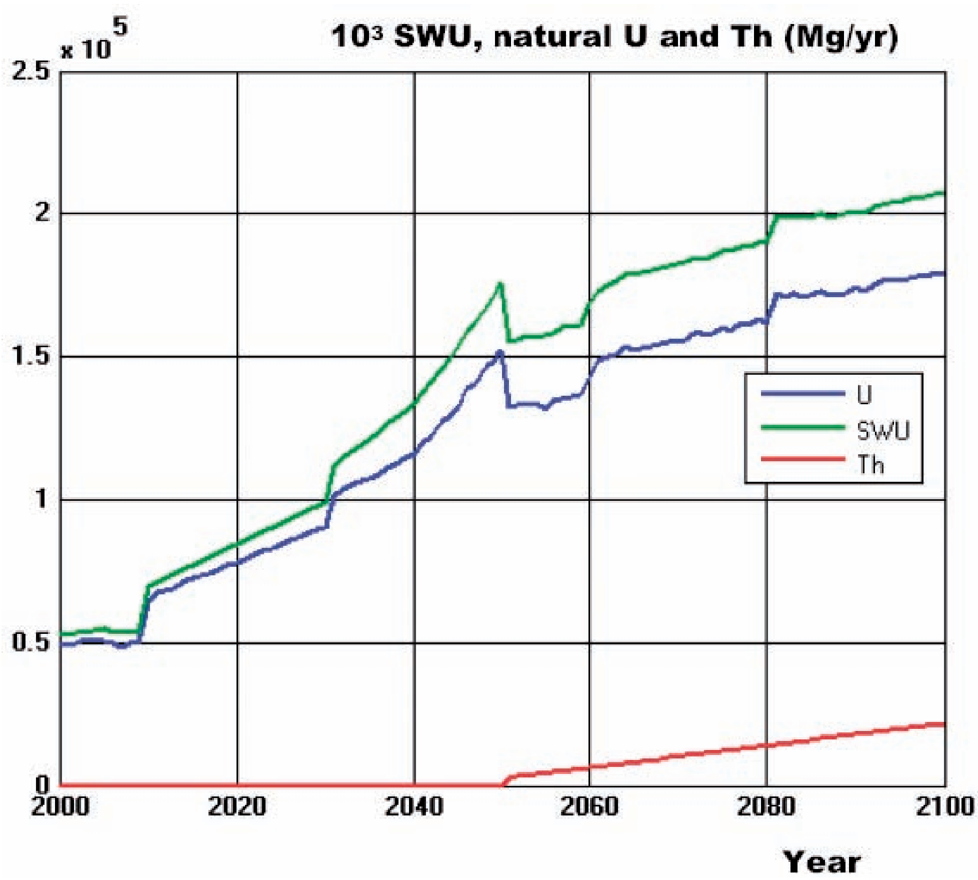

FIG. 20. Annual demand for natural uranium and thorium production and separation work in the HIGH growth scenario.

- — Challenges — technical, financial, infrastructure, etc. — of developing and deploying fast reactors of the type and at the rates assumed;
- — The requirement for the large scale reprocessing of spent fuel;
- — Intra-regional and inter-regional transfers of irradiated and fresh fuels;
- — Intra-regional and inter-regional transfers of radioactive waste, including possibly both the high level waste and the long lived L&ILW from reprocessing;
- — Associated legal, societal, and regulatory considerations.

Some aspects of international transfers are discussed in Section 4 of this report.

3.4. THE USE OF FUSION NEUTRON SOURCES FOR BREEDING

As an alternative to deploying fast reactors with high breeding ratios, one could consider the use of thermonuclear fusion systems for breeding Pu and/or U-233 fuel for use in fission reactors. While such a development is, at present, conceptual, computer analysis can be used to demonstrate the impact of deploying such a hybrid system. In such a hybrid fusion–fission nuclear energy system, the fusion reactor would be used primarily for the production of neutrons rather than conversion of energy per se and so its design and operation would not be determined by energy efficiency requirements but, instead, by its capability to generate fresh fuel (breed fissile material) for use in fission reactors.

One thermonuclear fusion reaction (deuterium reacting with tritium) produces one high energy neutron (14.1 MeV) and one high energy alpha particle (3.5 MeV). The subsequent absorption of the neutron in a blanket of fertile material can produce, via spallation, up to 1.7 fissile isotopes per high energy neutron. Fission of this fissile

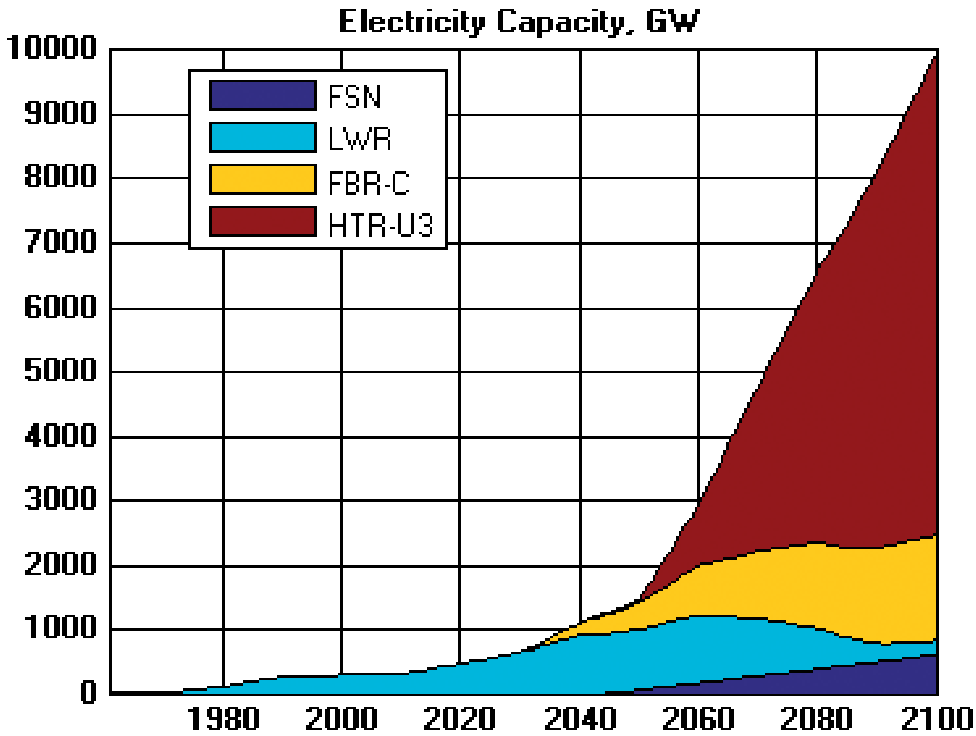

FIG. 21. Global nuclear energy installed capacity by reactor type as a function of time for the HIGH growth scenario, with fusion reactors used to breed fissile material for use in fission reactors.

isotope (produced in the fusion reactor) by one neutron in a thermal reactor will generate about 350 MeV of thermal energy. Thus, in a hybrid fusion-fission system the power of the fusion reactor can be relatively small, compared with that of the fission reactor. From this viewpoint, it is expedient to use Th-232 as the fertile isotope, which minimizes the thermal energy of the fusion reactor.

To illustrate the benefit that might be obtained from deploying fusion reactors for breeding fissile material, a nuclear energy system including fusion neutron sources (FNS) used for breeding U-233 in liquid (molten salt) Th fuel blankets with deeply suppressed fission (on-line removal of protactinium-233 from the blanket) was modeled. The U-233 from the fusion breeder was subsequently mixed with U-238 for use in LWRs and/or fast reactors or with Th for use in high temperature reactors. Such a nuclear energy system is shown in Fig. 21, which shows the installed capacity of each reactor type as a function of time, meeting the capacity demand for the high growth scenario. Note that in this example the fast breeder reactor has a breeding ratio of ~1 compared with a breeding ratio of 1.6 for the system described in Section 3.3. In the system shown in Fig. 21, fusion neutron sources and high temperature reactors operating on the U-233-Th cycle would start to be deployed around 2050 and fast reactors would be deployed beginning in 2030.

Figure 22 shows the corresponding annual demand of natural U and Th, as well as the uranium enrichment demand as a function of time. Annual consumption of uranium would peak in the 2040 to 2060 time frame and then would decline to about 20 000 Mg per year by 2100. The accumulated demand for uranium would reach 10 million Mg by 2100. The annual demand for thorium would increase steadily rising to about 140 000 Mg by 2100.

Since the share of fusion neutron sources in the system would be small (below 10%), they could be built in a limited number of countries, for instance, countries hosting international/multinational fuel cycle centres. Such a development could have significant benefits in the areas of proliferation resistance and environment, since the amounts of both Pu and minor actinides would be less by an order of magnitude, compared with nuclear energy systems with large scale use of fast reactors operating on the U-Pu fuel cycle.

It should be noted that the structure of nuclear energy systems with fusion reactors used for fissile breeding would be qualitatively different from systems based on the large scale deployment of fission breeder reactors. This development strategy could utilize thermal reactors designed and operated to minimize the consumption of fissile

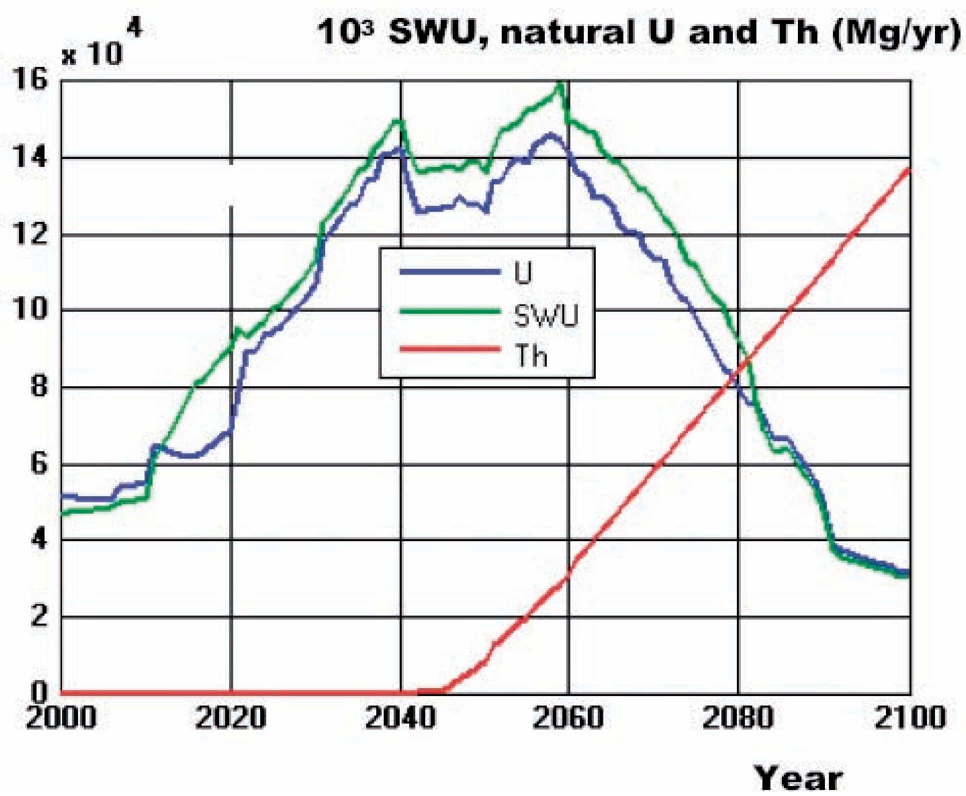

FIG 22. Annual demand of natural U/Th production and separation work for the HIGH scenario in case of use of a fusion neutron source.

isotopes by maximizing fuel burnup, which would also minimize the production of fresh fissile isotopes. Such a nuclear energy development concept has not been considered in detail; however, its potential advantages in the field of fuel supply — and, therefore the potential scale of nuclear energy development — makes it expedient to consider it in greater detail, in a subsequent study.

3.5. SUMMARY

The evolution of different nuclear energy systems, comprising different combinations of thermal and fast reactors, have been modeled to the end of the twenty-first century for three different nuclear energy demand scenarios, so-called LOW, MODERATE and HIGH growth rates. The LOW growth rate scenario assumes that the demand for nuclear energy will increase by a factor of 2.7 by 2050, compared with the installed capacity as of 2007 and by a factor of about 7 by the end of the century. The MODERATE and HIGH growth scenarios anticipate an expansion in nuclear capacity by a factor of 13 and 27, respectively, by 2100.

In all scenarios the components of the nuclear energy systems were chosen so that the total accumulated demand for natural uranium until the end of the century was constrained to be less than or equal to 20 million Mg.

In the LOW growth scenario, this constraint could be met using only thermal reactors operating on a once through cycle without reprocessing. None-the-less, the accumulated demand for uranium, as of 2100, could be reduced by about a factor of 2 by introducing fast reactors, with a breeding ratio of ~1, operating on a closed fuel cycle beginning around 2030. Such introduction will also reduce significantly the amount of SNF for final disposal.

In the MODERATE and HIGH scenarios, the uranium demand constraint can be met with the deployment of fast reactors with high breeding rations, assuming that these reactors are initially started with the plutonium extracted from spent fuel of thermal reactors. In this case the higher breeding ratio reactors are required to ensure that sufficient fissile material is available for the startup of new fast reactors in a rapidly expanding fleet since the small fraction of plutonium and fissile uranium contained in the spent fuel of thermal reactors is very small. Thus, deploying such fast reactors is sufficient for keeping the accumulated demand for uranium within the targeted value but, as shown in Annex IV, it is not a necessary condition if one considers a uranium startup for the fast reactors, at least for the MODERATE scenario. The development of fusion reactors for use as neutron sources for breeding fissile materials is also attractive from the viewpoint of conserving uranium resources.

By the end of the century, all three scenarios have a common trend — the capacity structures will become similar among the 9 regions used in this study. It has been assumed that for the MODERATE growth and HIGH growth scenarios, fast reactors will be deployed in all regions.

On the basis of a Joint Study of fast reactors operating on the closed fuel cycle [20] it seems likely that the first commercial fast reactors will be sodium cooled reactors utilizing oxide fuel. Such reactors can make a useful contribution to conserving uranium resources, but if nuclear fission is to be more widely used the development and eventual deployment of other types and designs of fast reactors with low specific capital costs, comparable to those of thermal reactors, will probably need to be pursued, coupled, possibly, with the use of the Th fuel cycle, and/or also the development of fusion neutron sources. As noted in Ref. [20], the attributes demanded of fast reactors may be different in different regions. Regardless, of the details, development of such systems will require substantial investments in research and development to first demonstrate feasibility and then to move the technology through the development cycle to commercial application (see Table 4.3 of Volume 1 of Ref. [21].

While the focus of this report is on the evolution of a mixed fleet of thermal and fast reactors that conserves uranium resources, and not on economic analysis, preliminary estimates of investment costs for deploying and then decommissioning the reactors and associated high level waste management facilities have been made (Annex V).

Many challenges both technical and non-technical would have to be overcome to develop and deploy fast reactors of the types and at the breeding rates assumed in the MODERATE growth scenario, and especially for the HIGH growth scenario.

4. INTERREGIONAL ASPECTS OF NUCLEAR ENERGY SYSTEMS

Analysis of nuclear energy development scenarios (Section 3) shows the potential importance of the global deployment of fast reactor technology and of the associated large scale reprocessing of spent nuclear fuel.

In this section we examine the implications of distributing such technologies among different regions, in terms of inter-regional transfers of uranium for enrichment and of fuel. These are presented in Sections 4.1 to 4.3 for the LOW, MODERATE, and HIGH growth scenarios, respectively. We take as a starting point the current status summarized in Fig. 23 (see also Table III–2 in Annex III).

Total capacity of fuel cycle facilities (enrichment E, reprocessing R, fuel fabrication F) is given in percentage of the global capacity, and the nuclear energy capacities (nuclear energy) are given in GW(e) as set out in Table 7. No official value of the enrichment capacity (E) in the South Asian region was available at the time the study was performed.

4.1. NUCLEAR MATERIAL FLOWS AMONG REGIONS — LOW GROWTH SCENARIO

Interregional natural U and nuclear fuel supplies under the LOW scenario are presented in Annex III for 2030 (Figs III–1 and III–2) and for 2050 (Figs III–3 and III–4).

In 2030, the Far East (FE) region would be the biggest net importer of fresh nuclear fuel, in spite of its large natural uranium resources, while North America (NA) and Eurasia (EA) would be the only exporter (EA would export twice as much as NA) of fresh fuel globally although they both have to import natural uranium (NA would have to import 5 times as much as EA). The FE region, together with Africa (AF) would supply its uranium mostly to Europe (EU) and North America (NA), where this uranium would be enriched and used for fuel fabrication. This distribution of fuel fabrication and supply would require a considerable increase in enrichment capacities, for

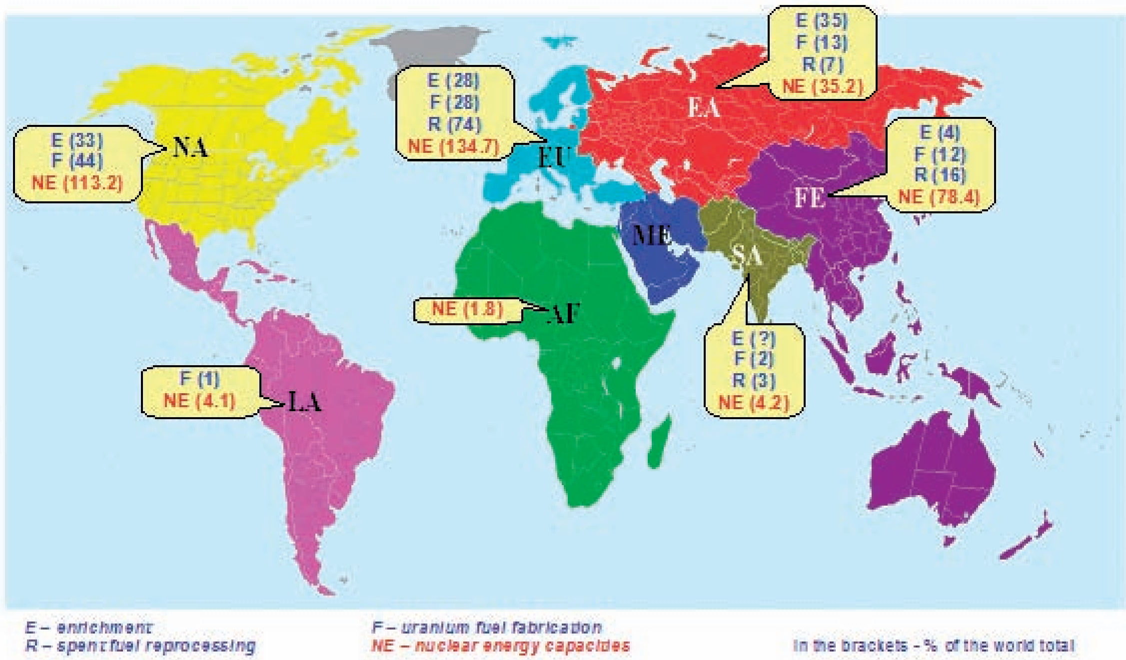

FIG. 23. Regional distribution of fuel cycle facilities (2008).

example from an available capacity of about 18 000 10^3 SWU/year in 2007 to about 35 000 10^3 SWU/year to be available in EA in 2030.

This LOW growth scenario assumes that the current structure of interregional supply of natural U and fuel is approximately maintained until mid-century. In 2050 Africa (AF) and Far East (FE) would be the principal purchasers of fuel, and they would also be the main suppliers of natural uranium to the world market. Regions such as EA, NA and EU would provide enrichment and fuel fabrication for fuel supply to other regions, as well as meeting their own needs.

Inter-regional natural uranium and nuclear fuel flows as of 2050 are shown in Fig. 24. The situation is somewhat similar to that for inter-regional transfers of oil, where over half of the oil consumed by regions is supplied from other regions. Thus some regions may be concerned about being dependent on other regions for the supply of uranium.

4.2. NUCLEAR MATERIAL FLOWS AMONG REGIONS — MODERATE GROWTH SCENARIO

Inter-regional supplies of natural uranium and nuclear fuel for the MODERATE growth scenario are presented in Annex III (Figs III–5 to III–10), together with interregional supplies of spent nuclear fuel (SNF) for reprocessing and the supplies of MOX fuel. Note that after 2050 interregional fuel flows under the MODERATE growth scenario (and also for the HIGH growth scenario) assume that the development and deployment, in South Asia (SA), of fast reactors with high breeding ratios and short storage and recycling times make this region self-reliant.

By the mid-century (2050) not all regions could be expected to have enough capacities to meet their own requirements and so some inter-regional transfers of recycled fuel would occur. However, the study shows for the MODERATE growth scenario (see Table III–7 in Annex I) that the scope of interregional recycled fuel supplies would be relatively small (about 1100 Mg of recycled fuel per year). Hence, all regions could be assumed to meet their own demand almost completely. The same is true for inter-regional supplies of SNF for subsequent reprocessing**.**

Inter-regional flows of uranium for enrichment and of fresh fuels are shown in Fig. 25 for the year 2050.

This MODERATE growth scenario assumes a fuel cycle concept where the regions that are the least prepared for full scale fuel cycle deployment (AF, ME, LA) start by developing their nuclear energy system based on enriched uranium and thermal reactors, and then subsequently establish regional capacity for reprocessing needed for fast reactors to be deployed later, given that their demand for recycled fuel before 2050 would be quite low.

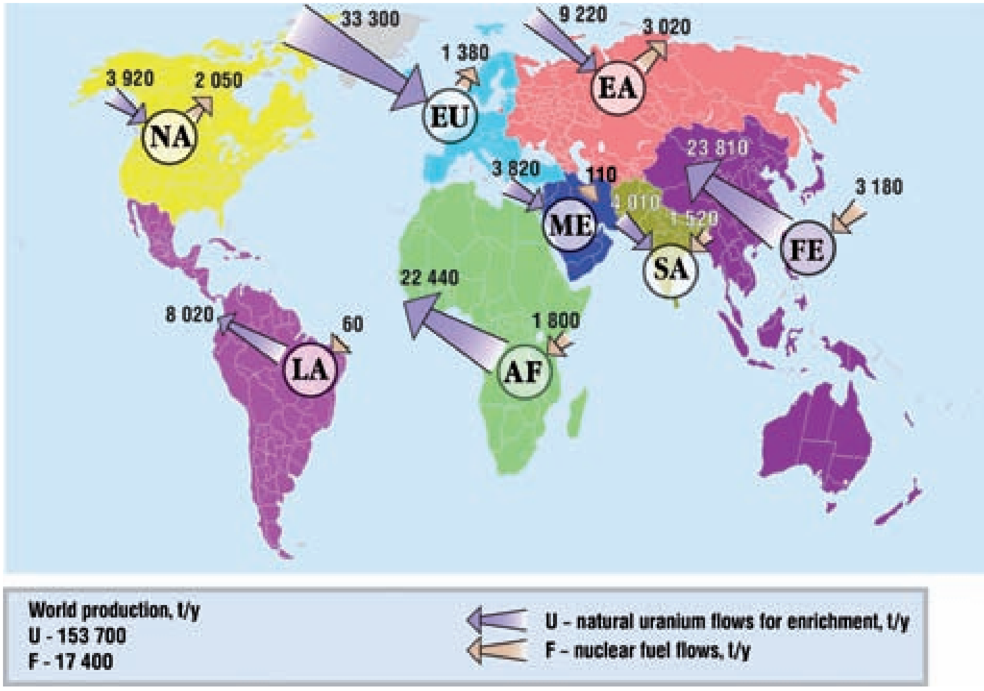

FIG. 24. Interregional flows of uranium and nuclear fuel under LOW scenario in 2050.

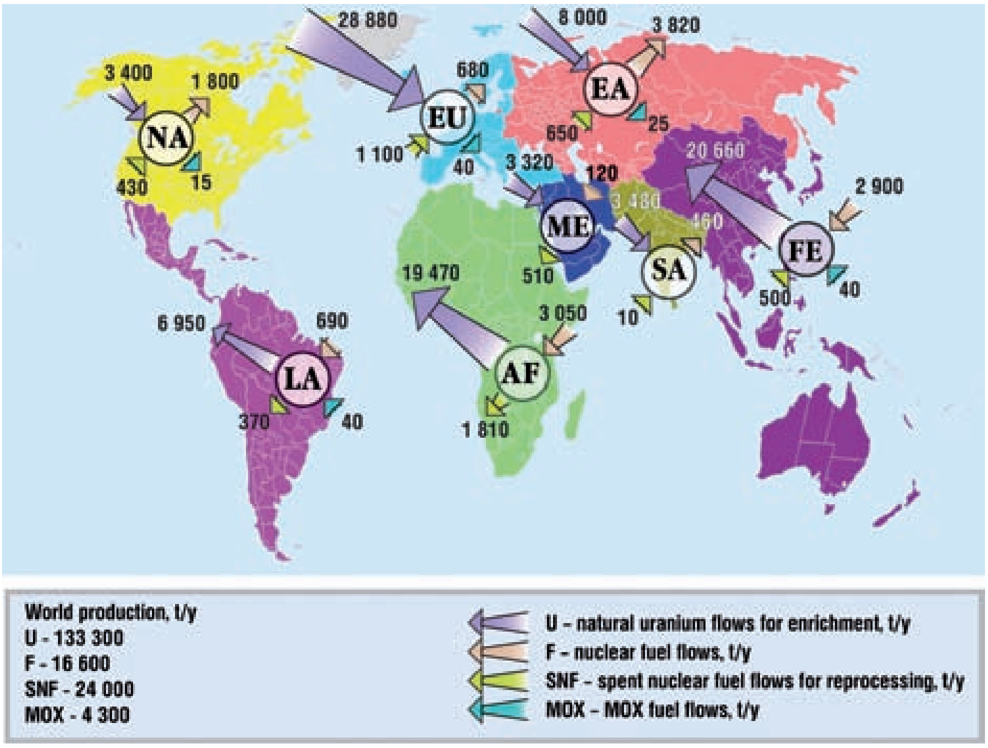

FIG. 25. Interregional flows of uranium, fresh, spent and recycled fuel under the MODERATE scenario in 2050.

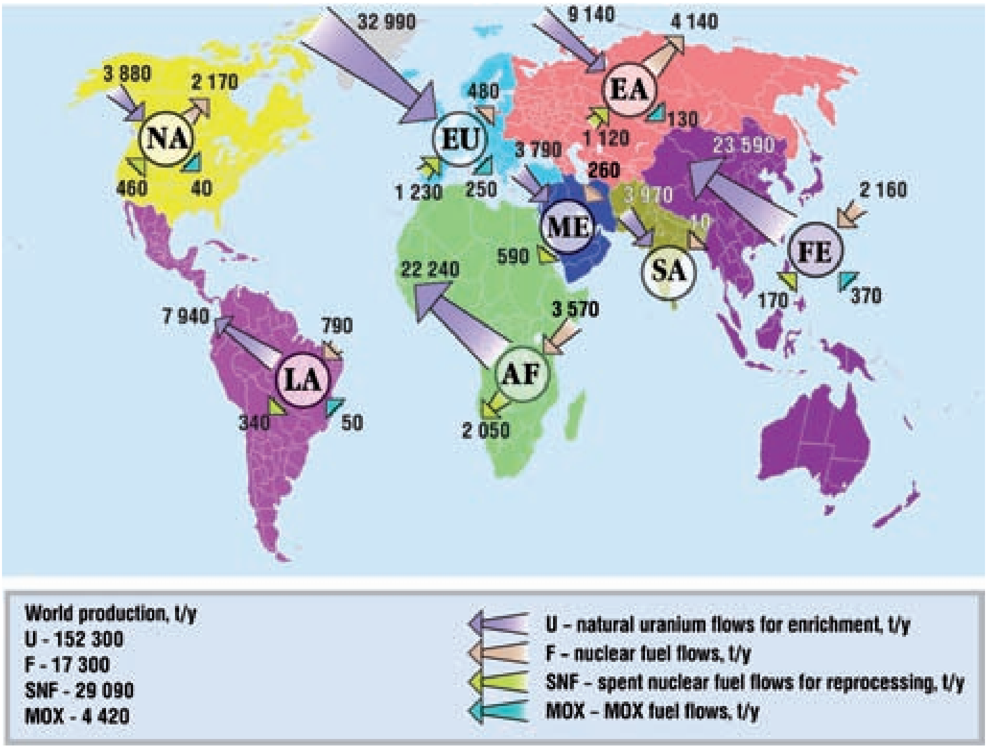

FIG. 26. Interregional flows of uranium, fresh, spent and MOX fuel under the HIGH scenario in 2050.

4.3. NUCLEAR MATERIAL FLOWS AMONG REGIONS — HIGH SCENARIO

Interregional supplies of natural uranium for enrichment, as well as supplies of nuclear fuel are presented in Annex III (Figs. III–11 to III–16) for the years 2030 and 2050, for the HIGH growth scenario, which also presents data on interregional supplies of spent fuel for reprocessing and recycled fuel supplies for the year 2050.

Interregional flows of uranium for enrichment, as well as fresh, irradiated and recycled (MOX) nuclear fuel, are summarized in Fig. 26 for the year 2050.

4.4. SUMMARY

For the LOW growth scenario and its once-through fuel cycle, the percentage of inter-regional supplies of natural uranium required to meet the global demand for fuel is about 50% in 2030, and drops to about 35% by 2050, assuming that the resource base in a given region would expand in parallel with the growth of the nuclear generating capacities in that region. At the same time, inter-regional fresh fuel supplies would represent 40% of global fuel supply by 2030 and over 50% by 2050. So, the attractiveness for uranium enrichment plants to be concentrated in large international centres would be strengthened, supported, in part, by non-proliferation and physical protection considerations. In such a case, the regions that provide uranium enrichment services would need to expand their capacity to meet a demand that is about twice as great as the intra-regional demand.

The deployment of fast reactors, spent fuel reprocessing and fuel fabrication using fissile isotopes bred in fast reactors in all regions under the HIGH nuclear energy growth development scenario — and in almost all regions already under the MODERATE growth scenario — would reduce the inter-regional flow of nuclear materials and could foster interest in establishing regional (and with international/multinational ownership) fuel cycle centres operating under international safeguards. The amount of inter-regional supplies of recycled fuel would be about 25% of the total consumption of recycled fuel. The amount of spent nuclear fuel transferred among regions would also be comparatively small — about 20% of its total production.

Ideas about international cooperation in the fuel cycle are not new. As far back as in the mid-1970s a study initiated by the IAEA concluded that a multinational approach to the organization of nuclear fuel cycles was preferable because of better economics from operations on a larger scale and improved proliferation resistance. More recently, an international study was carried out at the request of the Director-General of the IAEA, which performed a detailed analysis of multinational approaches [22]. Also, the existing system of international safeguards and control procedures applied to nuclear materials already represents a multinational approach. But further developments aimed at establishing several multinational/international fuel cycle centres encompassing interim spent fuel storage, reprocessing, and fuel manufacture including, possibly, final disposal of the associated wastes, will require comprehensive analysis of a variety of technical, political and social issues to strike the correct balance among competing national interests and concerns, and the geographic distribution of environmental burdens, industrial activities and economic and social benefits.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. OBSERVATIONS AND CONCLUSIONS

The study demonstrated a potential global evolution of thermal and fast reactors in terms of scenarios (hypothetical views of the future, of which an endless number exist). It postulated three different nuclear growth scenarios — LOW, MODERATE, and HIGH — and provided some examples of transition scenarios for moving from the current nuclear energy system based largely on a once-through fuel cycle with thermal reactors to a global nuclear energy system based on a closed fuel cycle with fast reactors. Other transition scenarios could be constructed using different combinations of reactors and fuel cycles.

In the low growth scenario*,* an increase of global nuclear power capacity from 370 GW(e) in 2009 to 2500 GW(e) by the end of the century was chosen. Assuming a free transfer of fuel services between regions, thermal reactors were shown to be sufficient to satisfy the demand until 2100 while also not exceeding the postulated limit of natural uranium consumption (20 million Mg). The study found that though establishment of the necessary spent nuclear fuel disposal facilities required in such a nuclear energy system might be problematic, international cooperation in establishing regional fuel cycle centres and associated waste disposal facilities might alleviate this concern. Introducing FBRs with a breeding ratio of ~1 beginning around 2030 could, in the low growth scenario, reduce the accumulated demand for uranium by about a factor of 2 as well as lead to a substantial decrease of the volume of spent fuel for final disposal.

In the moderate and high growth scenario global nuclear power capacity was assumed to reach 5000 GW(e) and 10000 GW(e), respectively, by the end of the century. The study demonstrated that closing the fuel cycle and deploying fast reactors in combination with the continued deployment of thermal reactors could accommodate such a large expansion of the role of nuclear power while keeping the uranium consumption within the limit of 20 million Mg. Thus, the study demonstrated that the constraint of reasonably priced fissile material is not a limiting factor for the sustainability of nuclear power. Further, the study illustrated, by means of scenarios, how all regions in the world could benefit from the deployment of such systems in an equitable manner.

Nonetheless, many challenges — both technical and non-technical — would have to be overcome to develop and deploy fast reactors of the types and at the rates assumed in the MODERATE growth scenario and especially for the HIGH growth scenario. While technical issues could still be solved with subsequent investment and R&D efforts within the given time, non-technical challenges could present a serious barrier to the rapid growth of nuclear power and may require appropriate international efforts.

The study assumed specific reactors types and fuel cycles. Other possible scenarios with compositions of different reactor types — including thermal reactors with high conversion ratios — and different approaches to the fast reactor first load — for example, enriched uranium — and also changing the assumptions about the impact on uranium resources of developing new lower cost extraction technologies would also be possible but they were not the subject of detailed considerations in this study. As well, the full potential of thorium was not taken into account. Regardless of the approaches followed, development of the technological basis for such reactors and fuel cycles needs to be continued so that they can be introduced on a commercial scale when needed. Further, a rapid expansion of fast reactors will demand the timely introduction of systems to provide the necessary fissile material for the first fuel load.

The deployment of reprocessing facilities and a combination of thermal and fast reactors in the chosen regions was demonstrated to be a sufficient condition to facilitate a more equitable distribution of nuclear energy use and hence wealth, consistent with the concept of sustainable development. The establishment of such facilities would be fostered by the development of an appropriate international framework addressing issues such as proliferation resistance, physical protection, and security of fuel supply leading to political acceptance at the national level.

If multinational fuel cycle centres are established under an appropriate international framework, proliferation resistance can be enhanced globally. In the absence of such multinational fuel cycle centres, a growing nuclear energy system with fast reactors and a closed fuel cycle would require the development of national facilities to serve domestic needs. Such a development would forego the economics of scale associated with larger multinational regional facilities, would increase the demand and cost for safeguards and would likely increase concerns about physical protection and proliferation.

Given the long lead times required to develop and new nuclear energy facilities bring them into commercial operation, and the costs involved, it is clear that substantial investment by governments will be required. In seeking to justify such investment, a common understanding of the need for innovative nuclear energy systems of the type described in this report and of the evolution/ transition of nuclear energy systems as innovative technologies are introduced, such as those presented in this report, needs to be developed. The strategic and policy issues associated with such nuclear fuel cycle transition scenarios have been discussed in a recent publication [21], and transition scenario studies are the subject of another report [22]. The current report and complementary studies also being carried out under the auspices of INPRO, the GAINS, FINITE, RMI, and ThFC studies [13] are helpful additions to this body of information.

5.2. RECOMMENDATIONS FOR FUTURE ACTION

In this study, the focus was on the development of a global nuclear energy system comprising a mix of thermal and fast reactors operating on a closed fuel cycle to improve the utilization of uranium for energy supply and to demonstrate that such nuclear energy systems are sustainable from the perspective of uranium resources. The INPRO methodology requires that other areas such as economics, waste management, proliferation resistance, security, environmental impact and safety be considered. Proliferation resistance has been touched upon in this report, but has not been considered in depth. Also, closing the fuel cycle opens up new options for waste management. Such options are discussed briefly in Appendix 10 where a number of potential benefits are identified but the analysis presented there is not fully consistent with the INPRO methodology. Therefore, it is desirable that, in due course, a comprehensive INPRO assessment, addressing all INPRO areas, be carried out on one or several of the systems of thermal and fast reactors considered in the present report[3].

The potential use of fusion reactors for the breeding of fissile material for fission reactors has been examined. Such a synergistic fusion-fission nuclear energy system has not been considered in detail in this study but may have potential advantages and such a nuclear energy system may be considered in more detail in a future study.

As was noted in Section 2, other options for improving the utilization of uranium can be considered, such as the development and deployment of high conversion thermal reactors, and use of enriched uranium for the first core load of fast reactors rather than relying only on plutonium recovered from spent fuel. Thus, the present study might be extended to include other combinations of reactors and fuel cycles.

Ideas about international cooperation in the fuel cycle are not new and the existing system of international safeguards and control procedures applied to nuclear material already represents a multinational approach. Further developments aimed at establishing several multinational/international fuel cycle centres encompassing interim spent fuel storage, reprocessing, and fuel manufacture including, possibly, final disposal of the associated waste, will require comprehensive analysis of a variety of technical, political and social issues to strike the correct balance between competing national interests and concerns, and the geographical distribution of environmental burdens, industrial activities and benefits. These issues can be of interest for further investigations.

[3] An initiative to clarify the waste management opportunities and challenges has been undertaken by the IAEA's Division of Nuclear Fuel Cycle and Waste Management with the co-operation of INPRO.

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Annex I

GLOBAL ENERGY TRENDS AND ROLE OF NUCLEAR POWER

Presently, 85% of the energy consumed in the world is based on fossil fuels. This share of fossil fuels is almost the same as in the early1970s. In the aftermath of the first oil crisis, the share of fossil fuels decreased due to the expansion of nuclear energy but then increased again in the last two decades due to low prices for fossil energy, stagnation of nuclear deployment and a very marginal growth of renewable energy. The increasing share of fossil fuels in recent years is also a consequence of the liberalization of the energy markets where nuclear energy and renewable energies require investment for which the financial return is uncertain or too slow for private business. In the case of nuclear energy, the lack of broad political support and long-term strategy has also affected private business willingness to invest.

There is a broad scientific consensus, though not totally uncontested, that anthropogenic greenhouse gases (GHG), primarily CO_2 from fossil fuels, contribute to global warming, which may have devastating effects on the world's climate. IPCC has concluded that the global emissions of CO_2 in 2050 need to be reduced by 50–80% compared to the 2000 levels if the global temperature is to be limited to 2.0–2.4 ºC [I–1, I–2]. This requires a drastic reduction of CO_2 emission from energy generation and consumption. Essentially, only the following emission reduction alternatives are being considered [I–1 – I–11]:

- Increased energy efficiency and reduced energy intensity;
- Carbon capture of fossil fuels;
- Nuclear fission
- Renewable energy sources (solar energy, wind, geothermal, biomass)
- In the longer perspective, innovative energy sources such as nuclear fusion.

Due to the scale of the required energy needs, all these alternatives are needed and complementary. They all require technical developments and breakthroughs, and massive investment and collaboration on a global scale. This has been recognized in the European Union and there is now a coordinated effort through the SET-Plan [I–7, I–8]. A full portfolio considering all options must be developed and deployed in order to meet the increased energy demand with a sustainable energy system. In the past decade there has clearly been stronger support for nuclear energy simply because it is needed to meet future energy demands. The increase in construction of NPPs and life extension in different nations can be directly followed from websites such as World Nuclear Association[4] and the IAEA's Power Reactor Information System[5].

The storylines in the various international energy scenario studies in recent years can be broken down into three main categories:

(1) 'Business as usual', where there is a large increase in the global energy demand and where fossil fuels remain the dominant energy source;
(2) High energy demand growth/low fossil;
(3) Moderate energy demand growth/low fossil.

A large nuclear expansion is foreseen in most of these scenarios except for some moderate energy demand growth scenarios that specifically assume a nuclear phase-out. For instance, in the scenarios that do not assume nuclear phase-out, nuclear energy is expected to increase by a factor 1.5–6 by 2050 [I–12 – I–14, I–4] and by a factor 8–14 in 2050 [I–12, I–13]. A more detailed discussion on the role of and targets for nuclear energy for the 2000 IPCC scenarios can be found in Ref. [I–16].

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[4] http://www.world-nuclear.org/

[5] http://www.iaea.org/programmes/a2/

The future energy mix will be determined by the availability of the technologies, the total cost, the environmental impact of the energy generation, the security of supply and societal acceptance. A future energy mix must also take into account the attributes of the different energy systems. An important feature of nuclear energy is that it provides a very stable base-load energy supply and therefore complements the non-hydro renewable energy sources whose main drawback is their intermittency. Nuclear energy is the only non-CO_2 emitting electricity generation technology deployed on a large scale today and which also can be significantly expanded. An expansion of nuclear energy, typically by a factor of two by 2030, is considered, by many, as necessary to limit the growth of greenhouse gas emissions in the near future. Such growth can be achieved by life extension and power upgrade of current generating reactors and construction of evolutionary thermal reactors [I–17 – I–21]. Between 2030 and 2050, the nuclear capacity should be increased to at least 1500–2000 GW(e) through further deployment of advanced thermal reactors and by the introduction of innovative fast reactors with nuclear fuel cycle closing by uranium and plutonium [I–20, I–21], and by considering thorium as fertile material. Fast reactor technology will allow much better use of uranium resources (up to a factor of 100) and a drastic reduction of radioactive waste, which would contribute to making nuclear a sustainable energy source. Thorium, which is much more abundant than uranium in the earth's crust, would provide additional natural fuel resources. In the second half of the century, many scenarios envisage an even larger expansion of nuclear energy.

Nuclear energy today is used mainly to produce electricity but relatively low temperature applications such as desalination and district heating are also used. Process heat for industrial application is another very large energy market — which is now totally dominated by fossil fuels — where nuclear energy could extend its contribution to curbing CO_2 emissions (e.g. [I–17 – I–22]). The HTRs using current technology can reach up to 800°C but the very high temperature reactors (VHTRs) are expected to attain temperatures of 1100ºC. Different applications for process heat include: desalination (200ºC), petroleum refinery applications (400°C), recovery of oil from tar sands (600–700ºC), synthetic hydrocarbon fuel (synthetic fuel) (600–1000°C), hydrogen production (60 –1000°C), coal gasification (900–1200ºC). Synthetic fuel can be rendered completely CO_2 neutral by making it from hydrogen and carbon dioxide. Reactors for heat process applications would normally be relatively small (400–600 MW(th)) and located directly in conjunction with the applications.

In several energy markets, the cost of nuclear energy has become competitive with that of fossil fuels (e.g. I–17, I–23 – I–26], but the high capital construction costs for new nuclear plants (typically 2/3 of the levelized cost) and the long return could be a barrier to expansion in a commercial market. Reduced construction times, simplified and harmonized licensing and standardized designs together with economy by larger-scale production following a nuclear expansion would reduce the costs; financial risks and, consequently, the cost of credit would decrease if a nuclear energy structure meeting the INPRO requirements were deployed [I–27]. A stable framework with a long-term perspective by governments is also very important for funding schemes, liabilities and radioactive waste policies. The construction of repositories for geological disposal of high level waste and spent nuclear fuel in the coming 15 years in Sweden, Finland and France, and possibly also in the USA, are very important steps towards gaining public and political support. Fast reactors will also require geological disposal but the volume, heat and radiotoxicity of the final waste may be reduced by up to two orders of magnitude. These amounts may be even further reduced if the transmutation of actinides and long lived fission products is developed and introduced with either fast reactors or accelerator driven systems.

The first 50 years of commercial nuclear energy was based on thermal reactors with uranium-based fuel, mainly with open fuel cycles. Apart from uranium mining, the nuclear industry was essentially a national business. This may not be the case in the twenty-first century, where fast reactors with advanced recycling and a much more complex fuel cycle infrastructure will be needed. Certain fuel cycle services need a sufficient critical mass which can be attained through international collaboration. Moreover, the expansion of nuclear power will also differ between the regions of the world with a shift in relative terms from the traditional nuclear regions (Europe, North America and Russia) to Asia and other fast developing areas. It is, therefore, clearly important to look at scenarios driven by global and regional needs as done in this study.

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Annex II

GROUPING OF COUNTRIES AND REGIONS

The countries and geographic regions included in each grouping are listed below (IAEA Member States are identified by asterisks)

North America (NA)	
Canada*	United States of America*
Latin America (LA)	
Anguilla	Haiti*
Antigua and Barbuda	Honduras*
Argentina*	Jamaica*
Aruba	Martinique
Bahamas	Mexico*
Barbados	Montserrat
Belize*	Netherlands Antilles
Bermuda	Nicaragua*
Bolivia*	Panama*
Brazil*	Paraguay*
Cayman Islands	Peru*
Chile*	Puerto Rico
Colombia*	S. Georgia & S. Sandwich Islands
Costa Rica*	Saint Kitts and Nevis
Cuba*	Saint Lucia
Dominica	Saint Pierre and Miquelon
Dominican Republic*	Saint Vincent & the Grenadines
Ecuador*	Suriname
El Salvador*	Trinidad and Tobago
Grenada	Turks and Caicos Islands
Guadeloupe	Uruguay*
Guatemala*	Venezuela*
Guyana	Virgin Islands
Guyane	

Europe (EU)	
Albania*	Liechtenstein*
Andorra	Lithuania*
Austria*	Luxembourg*
Belgium*	Malta*
Bosnia and Herzegovina*	Monaco*
Bulgaria*	Montenegro*
Croatia*	Netherlands*
Cyprus*	Norway*
Czech Republic*	Poland*
Denmark*	Portugal*
Estonia*	Romania*
Finland*	San Marino
France*	Serbia*
Germany*	Slovakia*
Gibraltar	Slovenia*
Greece*	Spain*
Greenland	Svalbard and Jan Mayen Islands
Holy See*	Sweden*
Hungary*	Switzerland*
Iceland*	The Former Yugoslav Republic of Macedonia*
Ireland*	Turkey*
Italy*	United Kingdom*
Latvia*	
Eurasia (EA)	
Armenia*	Moldova*
Azerbaijan*	Russian Federation*
Belarus*	Tajikistan*
Georgia*	Turkmenistan
Kazakhstan*	Ukraine*
Kyrgyzstan*	Uzbekistan*
Africa (AF)	
Algeria*	Malawi*
Angola*	Mali*

Eurasia (EA)	
Benin*	Mauritania*
Botswana*	Mauritius*
Burkina Faso*	Mayotte
Burundi*	Morocco*
Cameroon*	Mozambique*
Cape Verde*	Namibia*
Central African Republic*	Niger*
Chad*	Nigeria*
Comoros	Reunion
Congo*	Rwanda
Cote d'Ivoire*	Saint Helena
Democratic Republic of the Congo*	Sao Tome and Principe
Djibouti	Senegal*
Egypt*	Seychelles*
Equatorial Guinea	Sierra Leone*
Eritrea*	Somalia
Ethiopia*	South Africa*
Gabon*	Sudan*
Gambia	Swaziland
Ghana*	Togo*
Guinea	Tunisia*
Guinea-Bissau	Uganda*
Kenya*	United Republic of Tanzania*
Lesotho	Western Sahara
Liberia*	Zambia*
Libyan Arab Jamahiriya*	Zimbabwe*
Madagascar*	
Middle East (ME)	
Bahrain*	Oman
Iran, Islamic Republic of*	Qatar*
Iraq*	Saudi Arabia*
Israel*	Syrian Arab Republic*
Jordan*	T.T.U.T.J. of T. Palestinian A.
Kuwait*	United Arab Emirates*
Lebanon*	Yemen*

South Asia (SA)	
Afghanistan*	India*
Bangladesh*	Maldives
Bhutan	Nepal*
British Indian Ocean Territory	Pakistan*
Cocos (Keeling) Islands	Sri Lanka*
Heard Islands & McDonald Islands	

Far East and the Pacific (FE)	
Australia*	Niue
Brunei Darussalam	Norfolk Islands
Cambodia	Northern Mariana Islands
China*	Palau*
Cook Islands	Papua New Guinea
Democratic Peoples Republic of Korea	Philippines*
Fiji	Pitcairn Islands
French Polynesia	Samoa
Indonesia*	Singapore*
Japan*	Solomon Islands
Kiribati	Taiwan (China*)
Korea, Republic of*	Thailand*
Lao P.D.R.	Timor Leste
Malaysia*	Tokelau
Macau, China	Tonga
Marshall Islands*	Tuvalu
Micronesia, Fed. States of	US Minor Outlying Islands
Mongolia*	Vanuatu
Myanmar*	Vietnam*
New Caledonia	Wallis and Futuna Islands
New Zealand*	

Annex III

NUCLEAR FUEL CYCLE: CURRENT STATUS AND SCENARIOS

TABLE III–1. URANIUM RESOURCE DISTRIBUTION (%) [II–1]

Region	Identified resources	Total resources (Identified + Prognosticated + Speculative)
North America (NA)	13.9	26.4
Latin America (LA)	5.4	9.6
Europe (EU)	2.1	2.9
Eurasia (EA)	30.6	24.7
Africa (AF)	19.1	14.6
Middle East (ME)	2.1	1.9
South Asia (SA)	1.3	0.9
Far East and the Pacific (FE)	25.5	19.0

TABLE III–2. WORLD NUCLEAR ENERGY AND FUEL CYCLE: CURRENT STATUS AND REGIONAL DISTRIBUTION.

Process	Cumulative capacity of facilities in commercial operation*	Distribution by regions,%							
		NA	LA	EU	EA	AF	ME	SA	FE
Uranium production	43 328 MgU**	27.3	0.8	1.0	31.9	18.9	0.1	0.7	19.3
Enrichment	50 million SWU	33	—	28	35	—	—	—***	4
Uranium fuel fabrication	11500 Mg U/year (LWR) 4000 Mg U/year (PHWR)	44	1	28	13	—	—	2	12
Nuclear energy production	371.64 GW(e)	30.5	1.1	36.2	9.5	0.5	—	1.1	21.1
SNF reprocessing	6000 MgHM/year	—	—	74	7	—	—	3	16****

* According to [15].
** According to [14] data for 2007.
*** Small separation capacities also exist in Pakistan [III–2].
**** With account of Rokkasho plant being commissioned in Japan.

FIG. III–1. Interregional supplies of natural U for enrichment (2030, LOW scenario).

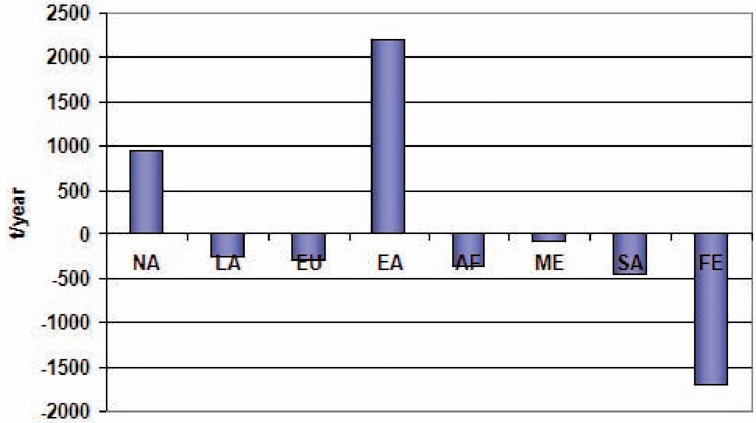

FIG. III–2. Interregional supplies of nuclear fuel (2030, LOW scenario).

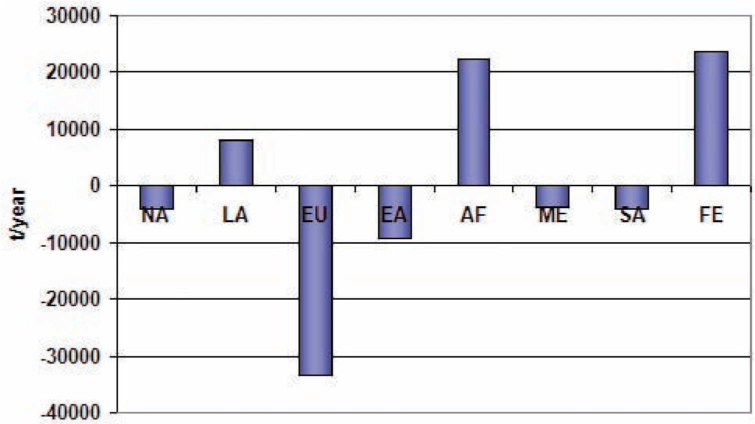

FIG. III–3. Interregional supplies of natural U for enrichment (2050, LOW scenario).

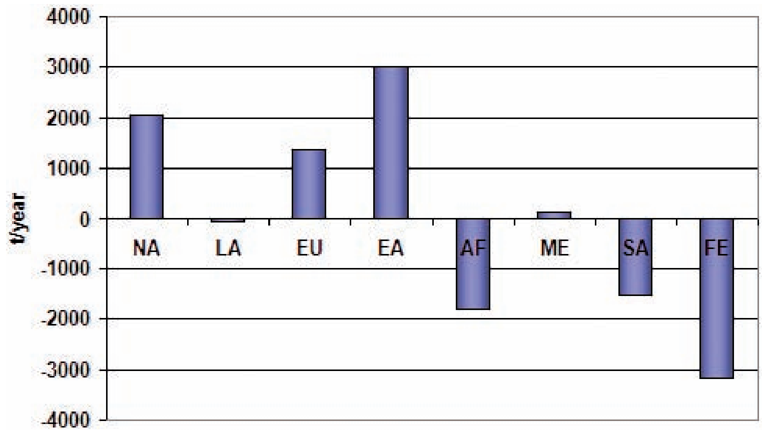

FIG. III–4. Interregional supplies of nuclear fuel (2050, LOW scenario).

TABLE III–3. PRODUCTION AND SUPPLY OF U AND NUCLEAR POWER PLANT FUEL (2030–2050, LOW SCENARIO)

	NA	LA	EU	EA	AF	ME	SA	FE	Total
Natural U production by regions, t/year									
2007	11 850	340	449	13 286	8183	20	310	8350	43 328
2007*	(–12 875)	(–430)	(–21371)	(7156)	(7893)	(15)	(–200)	(–5970)	(–25782)
* (Natural U production minus demand for the region [14]									
2030	10 286	3996	1554	22 644	14 134	1554	962	18 870	74 000
2050	40 581	14 757	4458	37 968	22 442	2921	1383	29 206	153 716
Natural U consumption by regions for enrichment and fresh fuel fabrication purposes, t/year									
2030	24 420	0	20 720	25 900	0	0	0	2960	74 000
2050	44 497	6742	37 755	47 193	0	6742	5394	5394	153 717
Fuel production by regions, t/year									
2030	3083	0	2616	3270	0	0	0	374	9343
2050	5037	763	4273	5342	0	763	610	610	17 399
Fuel consumption by regions, t/year									
2030	2127	256	2903	1066	373	89	453	2076	9343
2050	2984	828	2891	2326	1802	653	2126	3 789	17 399

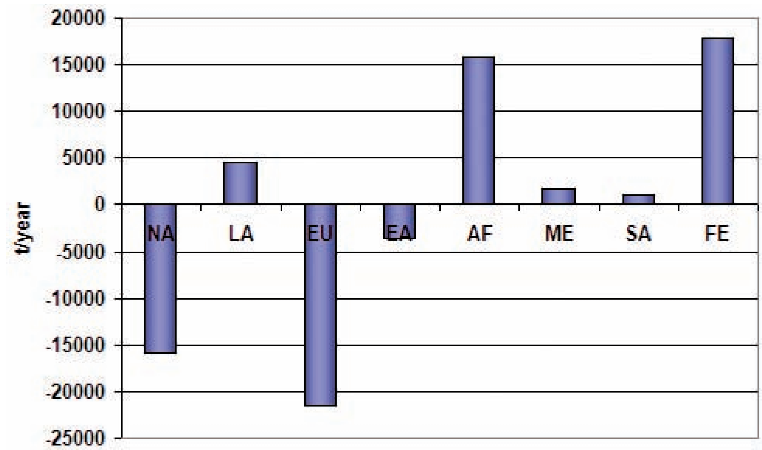

FIG. III–5. Interregional supplies of natural U for enrichment (2030, MODERATE scenario).

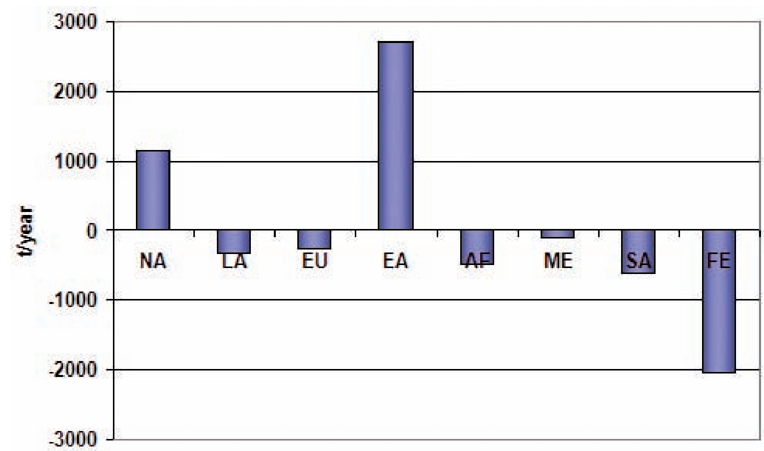

FIG. III–6. Interregional supplies of nuclear fuel (2030, MODERATE scenario).

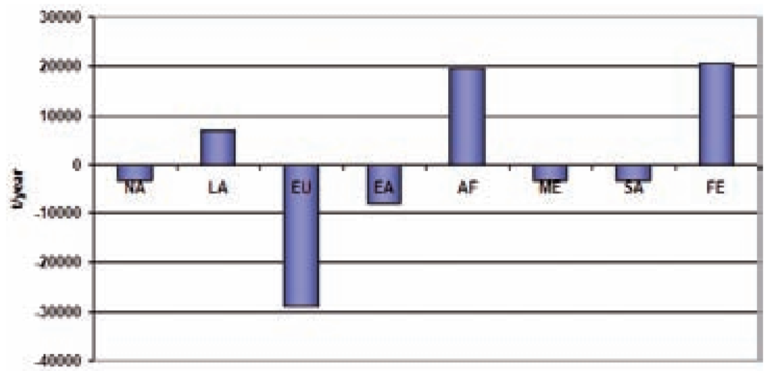

FIG. III–7. Interregional supplies of natural U for enrichment (2050, MODERATE scenario).

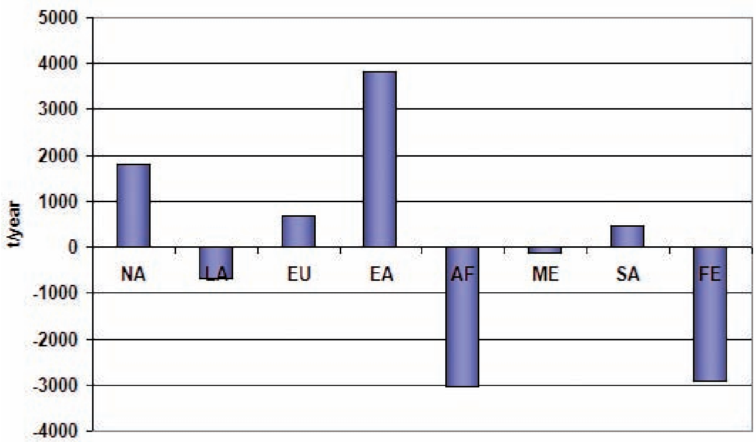

FIG. III–8. Interregional supplies of nuclear fuel (2050, MODERATE scenario).

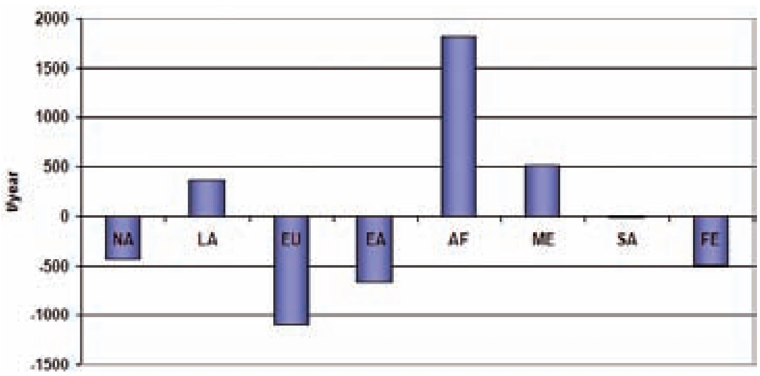

FIG. III–9. Interregional supplies of SNF for reprocessing (2050, MODERATE scenario).

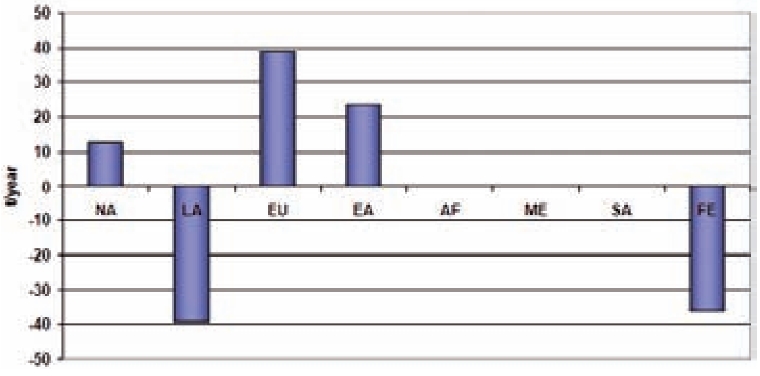

FIG. III–10. Interregional supplies of MOX fuel (2050, MODERATE scenario).

TABLE III–4. NATURAL U BALANCE BY REGIONS (MODERATE SCENARIO) LWR+LWR-M+SMR+FBR-S+FBR-A (BR=1.6), Mg/year

Year	Reactor	NA	LA	EU	EA	AF	ME	SA	FE
2030	Consumption	25 386	0	21 539	26 924	0	0	0	3077
	Production	10 693	4154	1615	23 540	14 693	1615	1000	19 616
2050	Consumption	38 598	5848	32 750	40 938	0	5848	4679	4679
	Production	35 202	12 801	3867	32 935	19 468	2533	1200	25 335
2100	Consumption	84 678	38 490	71 848	89 810	25 660	12 830	15 396	10 264
	Production	75 516	42 907	8295	70 653	41 763	31 465	25 744	54 349

TABLE III–5. PRODUCTION AND CONSUMPTION OF UOX FUEL BY REGIONS (MODERATE SCENARIO) LWR+LWR-M+SMR+FBR-S+FBR-A (BR=1.6), t/year

Year	Reactor	NA	LA	EU	EA	AF	ME	SA	FE
2030	Consumption	2428	309	3292	1120	461	106	116	2429
	Production	3386	0	2873	3592	0	0	0	410
2050	Consumption	2994	1414	3390	1265	3045	846	123	3485
	Production	4794	726	4068	5085	0	726	581	581
2100	Consumption	6194	4108	5450	2680	11 212	2828	56	11 711
	Production	10 735	4879	9108	11 385	3253	1626	1952	1301

TABLE III–6. PRODUCTION AND CONSUMPTION OF RECYCLED FUEL BY REGIONS (MODERATE SCENARIO) LWR+LWR-M+SMR+FBR-S+FBR-A (BR=1.6), Mg/year

Year	Reactor	NA	LA	EU	EA	AF	ME	SA	FE
2030	Consumption	0	0	0	0	0	0	271	0
	Production	0	0	41	27	0	0	203	0
2050	Consumption	548	82	695	430	0	0	1427	1133
	Production	561	43	733	453	0	0	1427	1097
2100	Consumption	1357	1009	2296	1618	476	374	7362	3457
	Production	1436	897	2513	1688	359	179	7362	3515

TABLE III–7. PRODUCTION AND REPROCESSING OF SNF BY REGIONS (MODERATE SCENARIO) LWR+LWR-M+SMR+FBR-S+FBR-A (BR=1.6), Mg/year.

Year	Reactor	NA	LA	EU	EA	AF	ME	SA	FE
2030	Consumption	2519	0	3391	1162	0	0	1053	1563
	Production	2290	203	2962	917	264	57	1053	1941
2050	Consumption	3841	720	5281	2641	0	0	5450	6074
	Production	3414	1089	4189	1973	1813	508	5441	5580
2100	Consumption	10 859	5666	14 164	8971	6610	1889	26 912	19 358
	Production	9232	6324	11 463	6979	10 480	3425	26 912	19 619

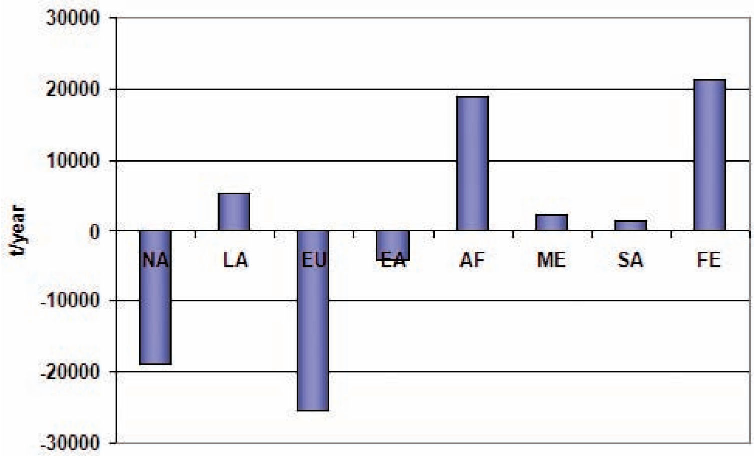

FIG. III–11. Interregional supplies of natural U for enrichment (2030, HIGH scenario).

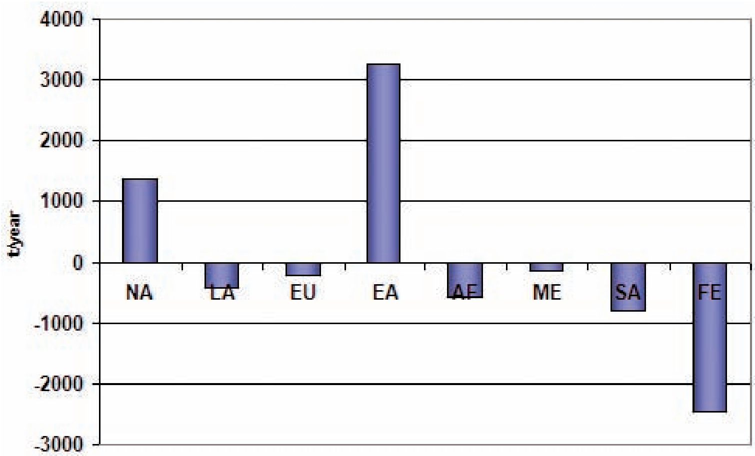

FIG. III–12. Interregional supplies of nuclear fuel (2030, HIGH scenario).

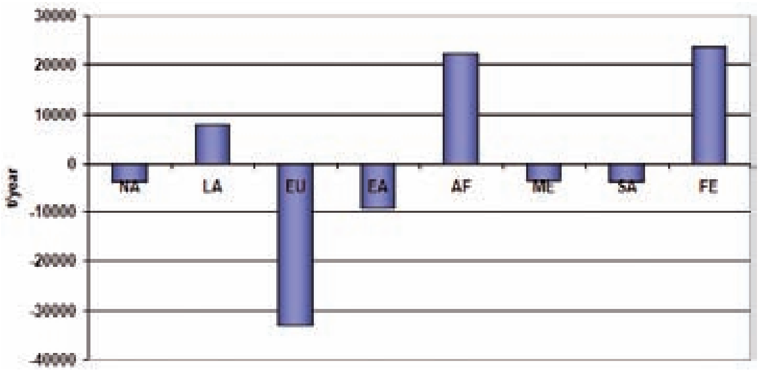

FIG. III–13. Interregional supplies of natural U for enrichment (2050, HIGH scenario).

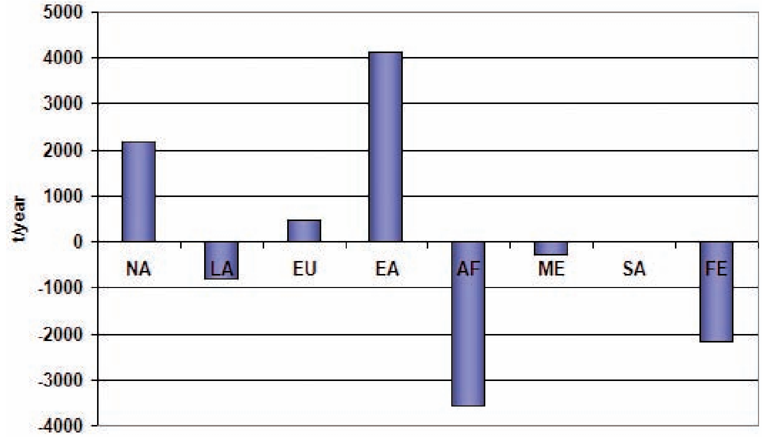

FIG. III–14. Interregional supplies of nuclear fuel (2050, HIGH scenario).

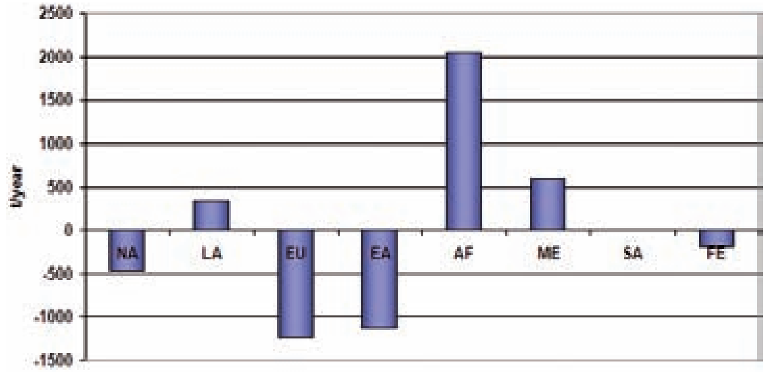

FIG. III–15. Interregional supplies of SNF for reprocessing (2050, HIGH scenario).

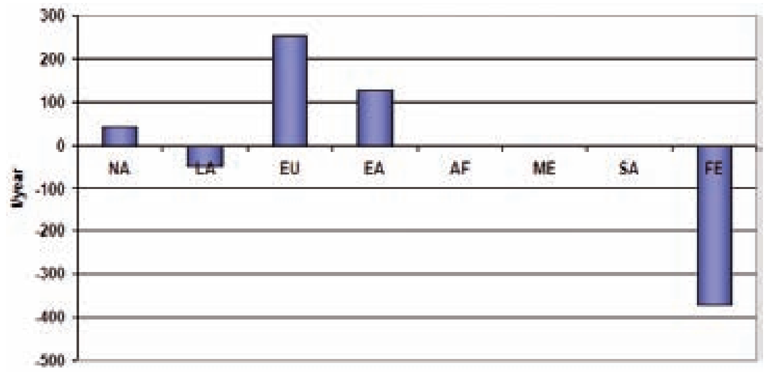

FIG. III–16. Interregional supplies of MOX fuel (2050, HIGH scenario).

TABLE III–8. NATURAL U BALANCE BY REGIONS (HIGH SCENARIO) WCR+WCR-M+SMR+FBR-A (BR=1.6)+FBR-A(TH)(BR=1.6)+HTR+HTR-U3, t/year

Year	Reactor	NA	LA	EU	EA	AF	ME	SA	FE
2030	Consumption	29 809	0	25 293	31 616	0	0	0	3613
	Production	12 556	4878	1897	27641	17253	1897	1174	23034
2050	Consumption	44 088	6680	37408	46760	0	6680	5344	5344
	Production	40 208	14 621	4417	37 619	22 236	2894	1371	28 938
2100	Consumption	43 480	19 764	36 892	46 115	13 176	6588	7905	5270
	Production	38 775	22 031	4259	36 279	21 444	16 156	13 219	27 907

TABLE III–9. PRODUCTION AND CONSUMPTION OF UOX FUEL BY REGIONS (HIGH SCENARIO) WCR+WCR-M+SMR+FBR-A (BR=1.6)+FBR-A(Th)(BR=1.6)+HTR+HTR-U3, t/year

Year	Reactor	NA	LA	EU	EA	AF	ME	SA	FE
2030	Consumption	2800	398	3735	1190	567	142	152	2907
	Production	3924	0	3329	4162	0	0	0	476
2050	Consumption	2837	1554	3777	1180	3563	1022	620	2765
	Production	5013	760	4254	5317	0	760	608	608
2100	Consumption	2266	2167	3234	1434	5133	2286	1706	3280
	Production	5218	2372	4428	5535	1581	791	949	633

TABLE III–10. PRODUCTION AND CONSUMPTION OF RECYCLED FUEL BY REGIONS (HIGH SCENARIO) WCR+WCR-M+SMR+FBR-A (BR=1.6)+FBR-A(Th)(BR=1.6)+HTR+HTR-U3, t/year

Year	Reactor	NA	LA	EU	EA	AF	ME	SA	FE
2030	Consumption	0	0	0	0	0	0	309	0
	Production	0	0	46	31	0	0	232	0
2050	Consumption	642	70	455	316	0	0	1704	1230
	Production	685	22	707	442	0	0	1704	858
2100	Consumption	3735	2360	3167	2160	4943	1244	10 704	8031
	Production	4616	1817	5088	3416	1817	363	107 04	8523

TABLE III–11. PRODUCTION AND REPROCESSING OF SNF BY REGIONS (HIGH SCENARIO) WCR+WCR-M+SMR+FBR-A (BR=1.6)+FBR-A(Th)(BR=1.6)+HTR+HTR-U3, t/year

Year	Reactor	NA	LA	EU	EA	AF	ME	SA	FE
2030	Consumption	2781	0	3744	1284	0	0	1202	1686
	Production	2491	251	3201	955	321	76	1202	2199
2050	Consumption	4945	873	5818	3200	0	0	6935	7319
	Production	4490	1211	4586	2077	2054	590	6935	7145
2100	Consumption	21 531	10 172	22 887	15 258	11 867	3391	45 519	38 908
	Production	17 652	11 775	16 160	10 418	24 785	7159	45 519	36 065

REFERENCES TO ANNEX III

[III–1] INTERNATIONAL ATOMIC ENERGY AGENCY, OECD NUCLEAR ENERGY AGENCY, Uranium 2007: Resources, Production and Demand, OECD 2008 NEA N 6345.

[III–2] OECD NUCLEAR ENERGY AGENCY, Nuclear Energy Outlook — 2008. OECD 2008, NEA No 6348, Paris (2008).

Annex IV

EXAMPLE OF AN ALTERNATIVE MODERATE GROWTH NUCLEAR CAPACITY SCENARIO

As was noted in Section 2 of the main text, the nuclear reactors selected for this study and presented in Tables 2 and 3 do not encompass the complete spectrum of the design options being considered and developed in Member States. For example, many future large capacity plants may, de facto, consist of a number of small or medium reactor modules. See, for example, Refs [IV–1, IV–2]. Additionally, not all SMRs will necessarily be water cooled reactors [IV–2]. Options such as the recycle of spent LWR fuel in HWRs might also have been considered. For fast reactors an alternative that was not included in the study was the use of enriched uranium fuel (enrichment lower or about 15% of U-235 by weight) for first startup with subsequent recycling of (Pu+U+MA) from the spent fuel. The latter option is discussed briefly below to illustrate the potential impact that changes in reactor options can have on the results.

It should be noted that each of the options for the first core loads of the fast reactor fleet, i.e. to start fast reactors using recycled plutonium from thermal reactors (explicitly considered in this study) or to use enriched uranium as the first core load, has its own benefits and disadvantages. For example, when using recycled plutonium from thermal reactors, large volumes of spent fuel reprocessing would be needed since there is less than 1% by weight of Pu in the spent nuclear fuel of LWRs considered. This option would, therefore, result in higher fuel reprocessing costs and limit the rate at which fast reactors can be deployed without introducing fast reactors with higher breeding ratios while developing such reactors presents its own challenges. The options of using enriched uranium for the first core load, which does not require initial reprocessing, would lower the demand for reprocessing capacity but require more enrichment capacity that may increase the front end fuel cycle costs. On the other hand, it would favour the deployment of fast reactors with a breeding ratio of slightly more than 1, which may be more readily achieved. Practical selection of a particular option would therefore be subject to many considerations — fuel-cycle infrastructure, economics, safety, proliferation resistance, etc. Such considerations could be assessed using the INPRO methodology, but this is beyond the scope of the present report. Rather, the aim was to illustrate only one aspect of changing the properties of the fast reactors used.

Hence, to illustrate how changes in the selection of reactor and fuel cycle options can influence outcomes, for the MODERATE growth scenario it was assumed that, in combination with using LWRs, fast reactors of type FBR-U are deployed beginning in 2025. FBR-U could be, for example, a lead cooled fast reactor design with a breeding ratio of 1.05. The reactor would be initially fuelled with enriched uranium (11.87% enrichment), and subsequently would shift to operating on its own recycled (Pu+U+MA), consuming only depleted uranium in the amount equal to the mass separated during recycling fission products. The characteristics of this reactor are set out in Table IV–1.

TABLE IV–1. BASIC REACTOR PARAMETERS OF FBR-U

Parameter		FBR-U
Capacity, GW(e)		1
Efficiency		0.435
Heavy nuclei load (Mg)	core	75
	axial blanket	—
	radial blanket	—
Fissile Isotope % — First Core U-235		11.87
Fissile Isotope % — Reload Core Pu-239 +Pu-241		9.26
Breeding ratio		1.05
Burnup, GW·day/t		72.8
SNF cooling time, years	core	3
	blanket	—

Figure IV–1 shows the evolution of the global energy system with this combination of reactor types. The calculations illustrate that even for the MODERATE growth scenario the deployment of fast reactors of type FBR-U, with a breeding ratio slightly greater than 1, can limit the demand for natural uranium until the end of the century to the target value of 20 million Mg.

Somewhat similar results could be achieved also with other types of coolant like lead-bismuth though the design due to its purpose (long life of the core) requires a bit higher enrichment of the initial fuel load.

It should be noted that these results were obtained using available design data of FBR-U type reactors and may be a subject of further specification on the basis of thorough neutron calculations.

For this case, the accumulated consumption of natural uranium would total 19.85 million Mg by the end of the century. At that time, thermal reactors would account for about 30% of the installed capacity while fast reactors would account for 70%.

For completeness, the annual demand of uranium and enrichment and the cumulative consumption of uranium are shown in Figs IV–2 and IV–3, respectively.

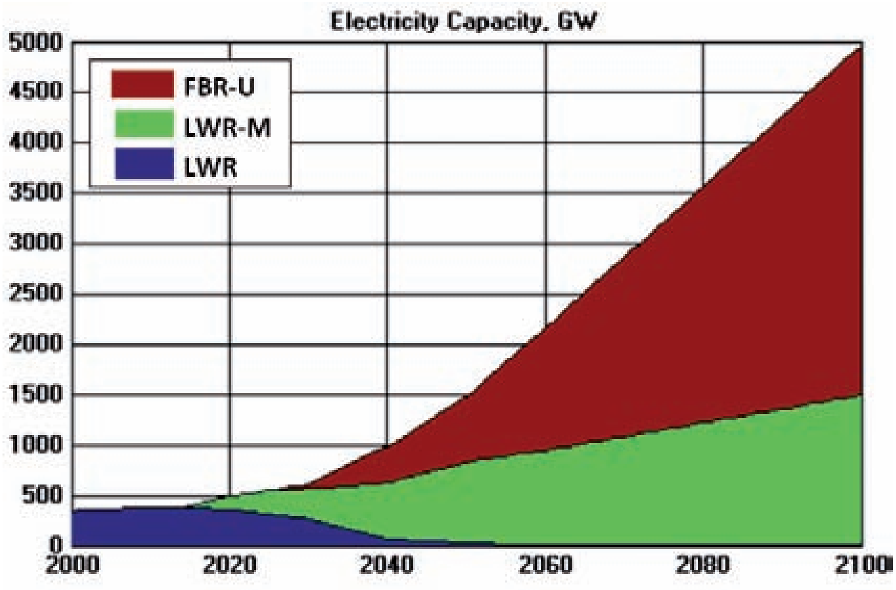

FIG. IV–1. Global nuclear energy installed capacity by reactor type as a function of time for the MODERATE growth scenario, considering the deployment of one type of fast reactor.

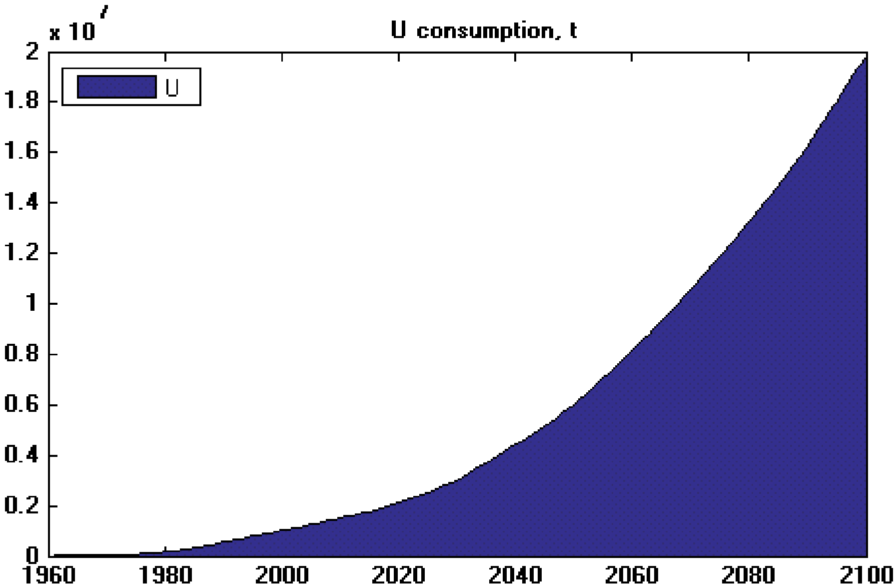

FIG. IV–2. Cumulative consumption of uranium resources for the moderate growth scenario.

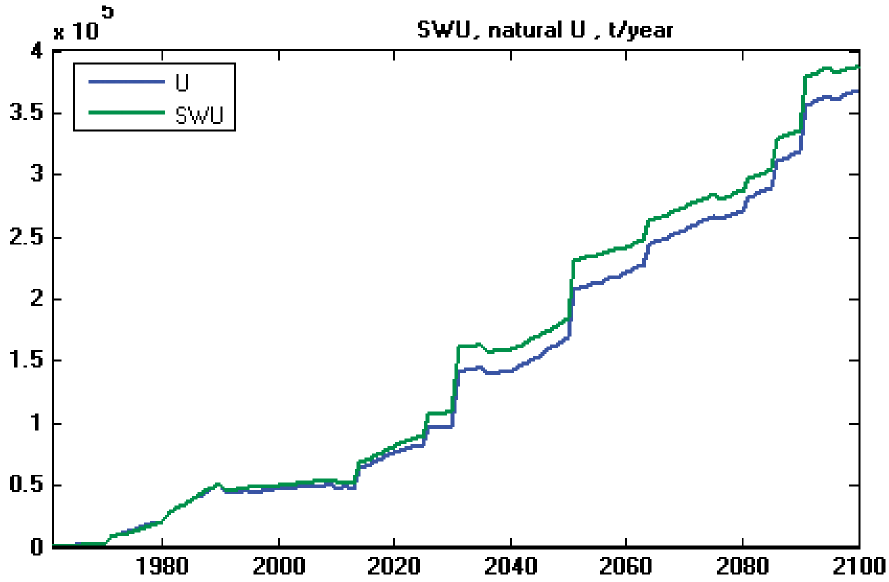

FIG. IV–3. Annual demand for natural uranium and enrichment in the MODERATE growth scenario.

REFERENCES TO ANNEX IV

[VI–1] INTERNATIONAL ATOMIC ENERGY AGENCY, Assessment of nuclear energy systems based on a closed fuel cycle with fast reactors, A report of INPRO, IAEA-TECDOC-1639, Vienna (2010).

[VI–2] INTERNATIONAL ATOMIC ENERGY AGENCY, INPRO Manual, TECDOC-1575, Vienna (2009).

Annex V

ASSESSMENT OF NUCLEAR ENERGY DEVELOPMENT INVESTMENTS

V–1. LOW SCENARIO

For the LOW scenario of nuclear energy development, the basic investment share would be connected with generating capacity construction, reactor decommissioning and construction of SNF repositories.

Figure V–1 shows investments required for reactor construction and decommissioning. Specific construction and decommissioning costs are shown in Table V–1.

The wave character of investments is determined by the need of higher rates of replacing capacities' commissioning – i.e. the delay of capacities' commissioning since 1990 has produced an 'investment wave', which would be present throughout the whole century.

Total investments from 2010 to 2100 would make US $7200 billion for nuclear power plant construction and US $900 billion for decommissioning.

The amount of spent nuclear fuel in long term repositories is shown in Fig. V–2.

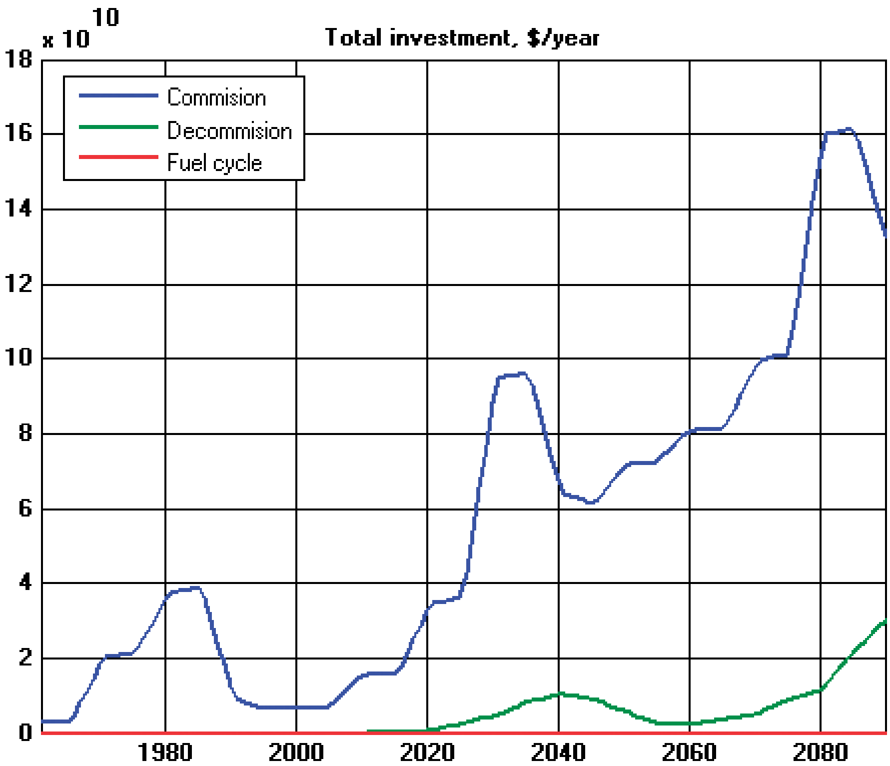

FIG. V–1. Nuclear power plant construction and decommissioning investments (LOW scenario).

TABLE V–1. SPECIFIC NUCLEAR POWER PLANT COSTS

	Construction costs, US $/kW(e)	Decommissioning costs, US $/kW(e)
LWR	2000	1000
LWR-M	2300	2300

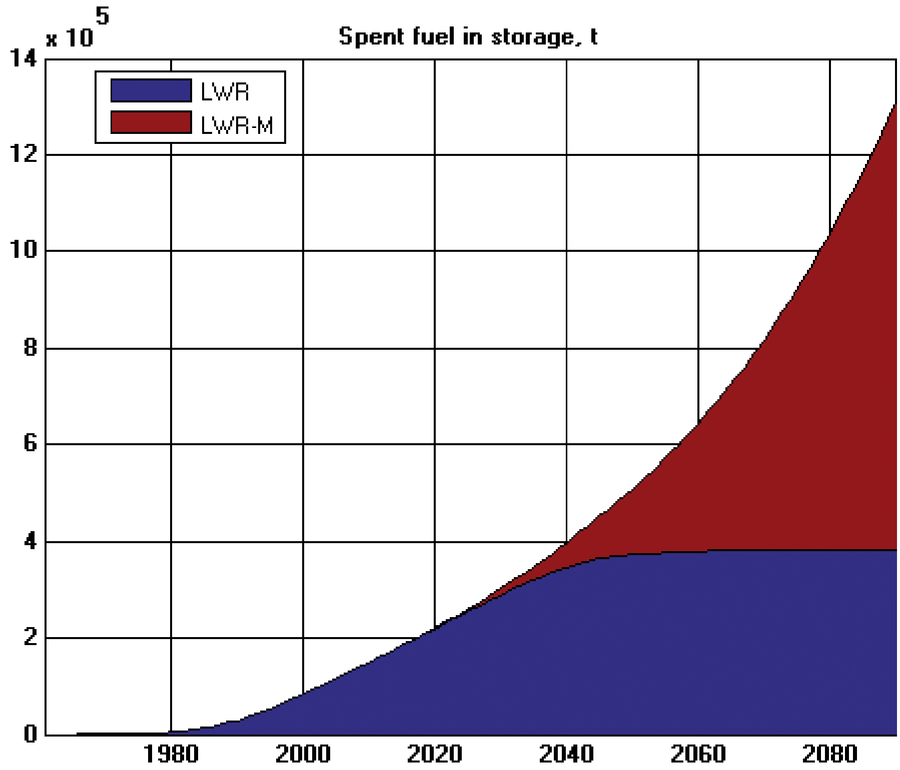

FIG. V–2. Amounts of spent nuclear fuel stored in long term repositories (LOW scenario).

This amount of SNF would require 19 Yucca Mountain type repositories (with a capacity of 70 000 Mg of SNF) to be built. Assuming the contemporary repository cost estimates (US $25 billion), total investments in repository construction would be about US $500 billion.

Total investments in the nuclear industry would reach about 0.18% of the total world GDP for the same period (assuming the GDP annual growth rate of 1%).

V–2. MODERATE SCENARIO

In this scenario, nuclear power plant construction investments would differ from the previous scenario by added investments in fast reactor and SNF reprocessing capacity construction. Table V–2 shows the respective specific costs.

Figure V–3 shows the investments in nuclear power plant construction and decommissioning, along with investments in fuel cycle capacities' construction.

Total investments from 2010 to 2100 would be US $15 000 billion for nuclear power plant construction, US $1600 billion for decommissioning, and US $120 billion for SNF reprocessing plants.

Total investments in nuclear industry would reach about 0.36% of the total world GDP for the same period (assuming the GDP annual growth rate of 1%).

V–3. HIGH SCENARIO

This scenario identifies nuclear power plant construction investments on the basis of the following fast and high temperature reactor cost parameters. The respective specific costs are shown in Table V–3.

TABLE V–2. SPECIFIC NUCLEAR POWER PLANT COSTS

	Construction costs, US $/kW(e)	Decommissioning costs, US $/kW(e)
FBR-S	3000	1500
SMR	2600	1000
SNF reprocessing plant construction investments, US $/t SNF		
2 million		

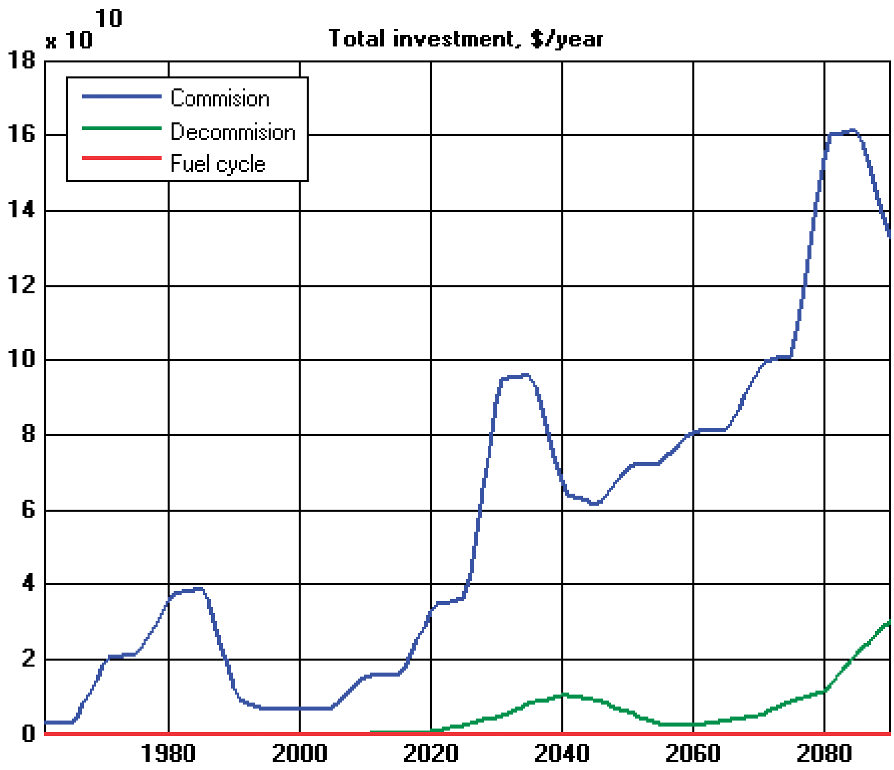

FIG. V–3. Investments in nuclear power plant construction & decommissioning and fuel cycle enterprises (MODERATE scenario).

TABLE V–3. SPECIFIC NUCLEAR POWER PLANT COSTS

	Construction costs, US $/kW(e)	Decommissioning costs, US $/kW(e)
FBR-A	4000	2000
HTR	3500	1500

Investments in fuel cycle plants are the same as in the MODERATE scenario.

Figure V–4 shows annual investments.

Total investments from 2010 to 2100 would be US $24 000 billion for nuclear power plant construction, US $2200 billion for decommissioning, and US $700 billion for SNF reprocessing plants.

Total investments in the nuclear industry would reach about 0.6% of the total world GDP for the same period (assuming the GDP annual growth rate of 1%).

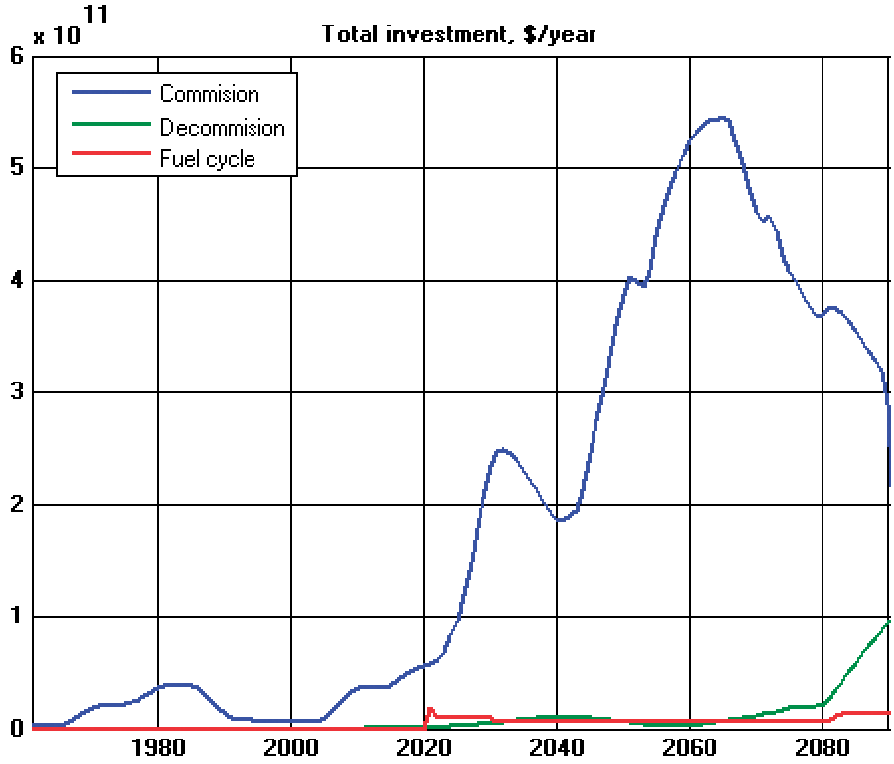

FIG. V–4. Investments in nuclear power plant construction and decommissioning and fuel cycle enterprises (HIGH scenario).

Taking account of the fact that in the last 35 years the share of energy expenses in the world GDP has varied from 4 to 10% (the higher value was achieved in the crisis periods of the 1980s and 2008), possible nuclear energy deployment costs, even under the HIGH scenario, seem to be affordable, at least in a global sense.

Annex VI

MATHEMATICAL MODEL OF DESAE CODE

The DESAE (Dynamics of Energy System of Atomic Energy) code is a system research model designed for developing the prospective nuclear energy scenarios on a regional as well as global scale. The DESAE model has been developed at the 'Russian Research Centre Kurchatov Institute', which is one of the research centres of the Russian Federation.

The mathematical model of the DESAE code, as currently developed, calculates the nuclear fuel cycle requirements, material balances and economic parameters in the framework of a nuclear energy scenario development, with a given combination of nuclear reactors during a specified time period.

DESAE provides the following options for analyzing the perspective nuclear energy development scenarios:

- To study the scenarios both on a regional and global scale;
- To vary the size and structure of the nuclear energy system, by commissioning different types of reactors at different rates;
- To modify the reactor characteristics and to study their influence on nuclear energy system parameters;
- To expand the existing databank by addition of new reactor types;
- To study both open and closed fuel cycles;
- To alter the spent nuclear fuel recycling capacity and external fuel cycle duration;
- Using the code in an interactive mode with a typical estimated run time of about one minute.

DESAE uses a flexible nuclear energy structure that is used for calculations on a regional as well as global level. Regional specifications are reflected in the initial input data, which specifies the nuclear power plant types, capacities, reprocessing plant capacities and so on. The integrated results of regional calculations are used to carry out calculations at the global level. At the global level, the regional commissioning programme of nuclear power plants and development of fuel cycle plants are summed automatically, based on the initial data given for separate regions.

There is an option for carrying out global scale calculations in parallel with the regional calculations by using the initial data specific to global scale calculations alone. As a rule, global calculations are subjected to less uncertainty, since assessments of regional resources are very uncertain in comparison with integral results. Most of these assessments were made in different institutes that are concerned with global consideration of nuclear energy. This allows setting out results in accordance with existing data in more detail. Such a scheme of calculation is convenient for analysis of inter-regional transport flows of fresh and spent nuclear fuel, natural uranium deliveries from region to region.

To begin, as is customary, global calculations are carried out, and also for each region individually. The regional results are then adjusted to be consistent with the global result. For example, it is interesting to note that, given different regional expectations of nuclear energy development as initial data, in a number of cases the total resource requirement considerably exceeds the result from an assessment made at the global level. In such a case, an algorithm is applied to force consistency between results at the global and at the regional levels.

DESAE has a provision for saving earlier calculated variants, and also allows viewing the results both in graphic and Excel mode.

The overall nuclear energy structure adopted in DESAE for carrying out calculations is shown in Fig. VI–1. The diagram of material (isotopes) flow realized in DESAE is presented in Fig. VI–2.

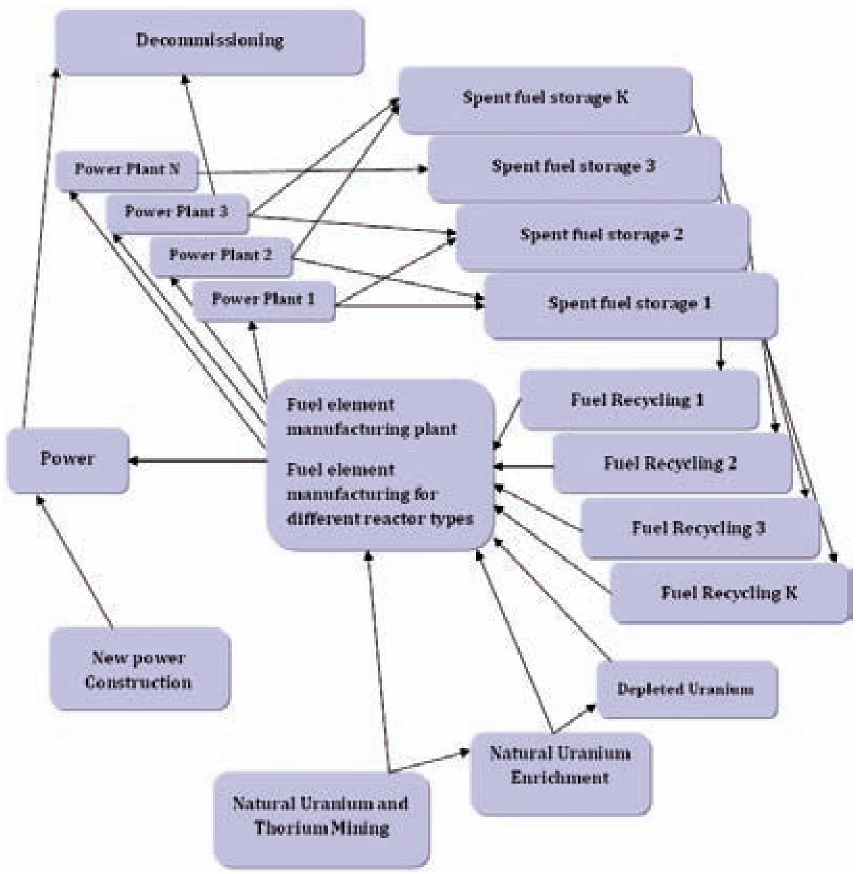

FIG. VI–1. Structure of the DESAE mathematical model.

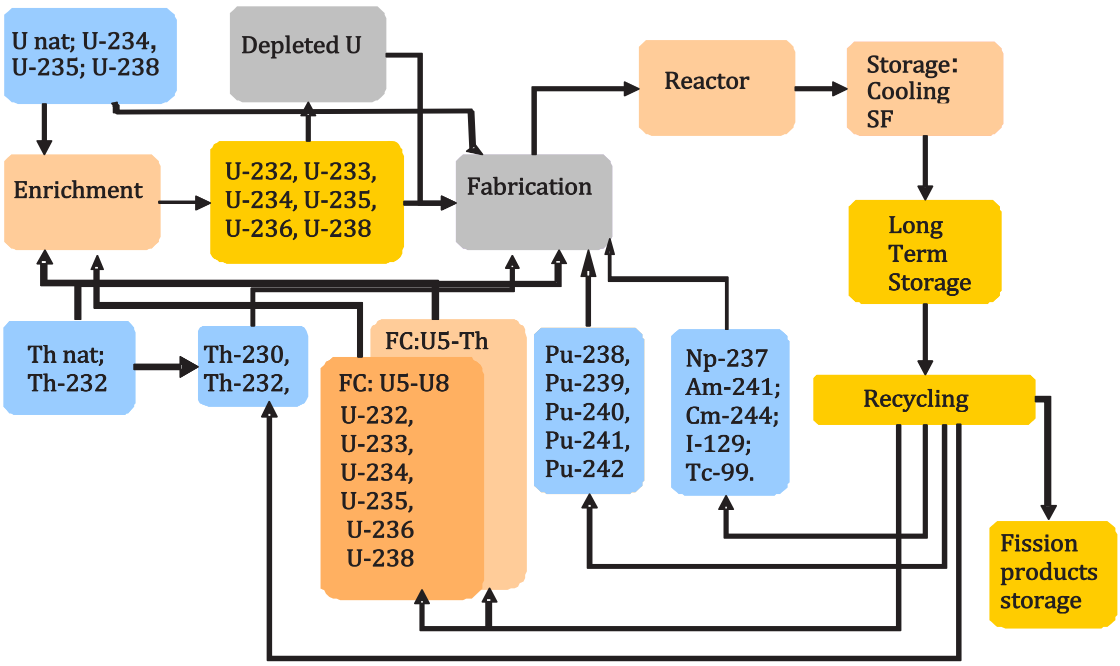

FIG. VI–2. Isotope flow diagram in DESAE.

Annex VII

DESAE TRANSPORT MODEL

The amount of interregional transfers of different products of fuel cycle facilities is calculated using the DESAE-TRANSPORT module. It allows interregional supplies to be calculated against a given resource production and consumption scope in a region, as well as a matrix of interregional exchange priorities for this resource. The inter-regional matrix for exchange priorities is defined by the user based on his expert knowledge/judgements.

The main features of the calculation procedure are as follows:

The balance of a material resource (production minus consumption) can be calculated by equation (1):

$$\vec{C} = \breve{T} * \vec{P} \tag{1}$$

Where:

C ={c_1, $c_{2,}$…c_N} — vector, the components c_1, $c_{2,}$…c_N is consumption quantity of that resource in the region ‘i’.
P ={p_1, p_2…p_N} — vector, the components p_1, $p_{2,}$…p_N is production quantity of that resource in the region ‘i’.
Vectors **C** and **P** (consumption and production in the regions) are input data.

T = transport matrix with a dimension **N*N**. The elements of the matrix t_{ij} identify the fraction of the resource produced in the region ‘i’ to be consumed in the region ‘j’.

In order to balance, the sum of all consumption quantities in all regions should be equal to the total production quantity of that resource in the region ‘i’, i.e.:

$$\sum_{j=1,N_{reg}} t_{ij} = 1; \tag{2}$$

$$\sum_{i=1,N_{reg}} t_{ij} p_i = c_j \tag{3}$$

This task cannot be resolved directly because the coefficients of the transportation matrix are unknown quantities, and their number is equal to the square of the number of the regions and hence the number of equations is less than the number of unknown quantities.

In order to solve the problem the following procedure was adopted. The expert defines the exchange priorities matrix $\mathbf{T_0}$, where the expert identifies from which regions to what regions transportation of the resource would be preferable. There is no need to fulfil equation (2) while forming the exchange priorities matrix $\mathbf{T_0}$. The coefficients can be chosen arbitrarily. The code makes normalisation automatically.

In further calculations the coefficients t_{ij} are iteratively matched in order to fulfil the balance conditions of equations (1) and (2), and in such a way that the difference between the calculated coefficients and those defined by the expert would be minimal, i.e.:

$$\sum_{i,j=1}^{Nreg} (t_{ij} - t_{ij}^{0})^2 - \min \tag{4}$$

where t_{ij}^0 are the normalized coefficients of exchange priorities matrix defined by the expert.

Annex VIII

THORIUM DEPLOYMENT POTENTIAL IN THE NEAR AND LONG TERM

Thorium and consequently U-233 utilisation is feasible in all existing and prospective reactor types, e.g. PWR, BWR, HWR, FBR and MSR. The incorporation of Th-U fuel in existing light water and heavy water reactors usually requires certain modifications in the engineered systems, reactor control and the reactivity devices, mainly because of the difference in the shares of delayed neutrons in U-235 and U-233 fission processes.

There are two principal ways of Th-U fuel introduction in existing and future reactors:

— Without reprocessing, i.e. in an open fuel cycle;
— With reprocessing of spent nuclear fuel (snf), i.e. in a closed fuel cycle.

The path without reprocessing envisages very high burnup (burnup up to ~170 MW·d/kgHM was investigated experimentally in the USA), long term operation of thorium loaded fuel assemblies (or fuel rods) to produce fissile material (mainly U-233 and some amount of U-235) from thorium, and afterwards produce heat by fission of this uranium in the same fuel elements.

The other path implies irradiation of thorium assemblies in a reactor, consecutive extraction of uranium, fabrication of new Th-U assemblies to be inserted in the same or another reactor. An important feature of the last approach is that according to preliminary studies one is able to reach a breeding ratio equal to 1 in HWRs, i.e. this option may allow building a sustainable closed fuel cycle using proven thermal reactor technology.

For some of the thorium fuel cycles, however, only reactor physics studies have been carried out and a lot of other technological developments are needed before these could be implemented. On the other hand, concepts destined mainly for consumption of U-233 and less for breeding, such as the Indian Advanced Heavy Water Reactor (AHWR), designed to produce nearly two-thirds of its power from thorium based fuel, have already been well developed and are close to reaching the construction stage.

Utilisation of thorium in the fuel cycle gives a number of opportunities for comparing to uranium one through fuel cycle or uranium-plutonium closed fuel cycle, e.g.:

— No enrichment is required in the thorium fuel cycle, and fewer conversion processes are required for developing mined thorium into fuel forms ready for first irradiation, in comparison with conversion of mined uranium into ‘conventional’ fuel form of UO_2.
— Use of U-233/Th-232 composition in fuel means the absence of U-238 in ‘fresh’ fuel and consequently decreases the amount of minor actinides in SNF; thus, from a waste management point of view the SNF from thorium fuel contains less long lived radioactive products.
— The ratio of neutron capture by fertile material to neutron loss (capture) in parasitic materials is higher for Th-232 compared to U-238, because thorium has approximately a 2.5 times higher neutron capture cross-section in a thermal neutron spectrum and approximately three times lower resonance integral.
— Reduced production of higher isotopes in the Th-U fuel cycle compared to U and U/Pu cycles because of lower non-fissile absorption of neutrons in U-233 than in U-235 and Pu-239 while the fission cross-sections are comparable. This feature leads to two advantages, namely, it enhances the ease of multiple recycling of U-233 compared to plutonium and also decreases the amount of minor actinides in spent fuel.
— The melting point of thorium dioxide (ThO_2) is more than 520ºC higher than UO_2, ThO_2 is also a chemically more stable substance than UO_2, and it possess better thermal conductivity (10 to 15% higher) as well as a lower thermal expansion coefficient. These features provide higher safety margins in fuel rod design (e.g. against fuel melting) and opportunities for increased economics in reactor design (i.e. high burnup and high thermal efficiency).
— SNF of Th-U fuel cycle is less attractive as potential raw material for nuclear weapons than uranium or uranium-plutonium spent fuel because of the admixture of U-232 whose radioactive decay chain contains emitters (particularly Tl-208) of high energy gamma radiation (2.6 MeV); this makes its transportation easily detectable resulting in an increase of proliferation resistance.

— Further enhancement of the proliferation resistance of U-233 compared with that of plutonium could be obtained by mixing it with relatively small amounts of depleted uranium to create ‘reactor grade’ U-233 but not ‘weapon grade’.

Using the existing well proven reactor technologies, use of thorium can thus provide opportunities to address some of the complex issues affecting the growth of nuclear deployment in several regions of the world. In this context, the changes of market environment or the impact of regulatory levers may increase the attractiveness of thorium utilisation in the near and middle term. Thus thorium will provide an option for contributing to large scale global deployment of nuclear energy to meet rising demand, as well as reduction in proliferation risk.

Just as development of fast breeder reactors, particularly those with high breeding ratios, involves challenges, one can also identify significant challenges that would need to addressed for the thorium fuel cycle, including the following:

— Irradiated Th-U fuel requires remote handling/control during transportation and reprocessing as well as during fuel fabrication because of the presence of the gamma ray emitters of the U-232 decay chain;
— The lack of commercial fabrication and reprocessing related infrastructure for thorium fuel, unlike the uranium plutonium fuel cycle infrastructure that was developed through investments made in the past.

The development of a thorium based closed fuel cycle demands significant efforts and apparently will be commercially available in a long term prospective comprising several new technologies in the area of fuel manufacture and fuel reprocessing which must be developed to provide the necessary economic competitiveness at the required scales of operation.

One should, however, recognise that the efforts in development of some ‘thorium independent’ technologies like molten salt reactors may significantly diminish challenges mentioned for the thorium fuel cycle, if not fully eliminate them.

The deployment of thorium on a large scale may help address concerns about the need for enhanced safety, security, waste management and proliferation resistance when the volume of nuclear energy related activities globally would increase multi-fold, as in the HIGH growth scenario Hence it is prudent to maintain thorium based nuclear energy systems as an option.

Annex IX

NUCLEAR ENERGY DEVELOPMENT SCENARIOS IN CHINA AND INDIA

IX–1. NUCLEAR ENERGY DEVELOPMENT SCENARIOS IN CHINA

The three step route for nuclear energy growth in China is staged with the development and deployment of thermal, fast and fusion reactors.

At present, mature thermal reactors are being deployed at an accelerating pace, and should be able to satisfy the near term needs. There are 11 LWRs in operation today with a total capacity of 9.1 GW(e) (not including the 6 reactors in operation and 2 under construction, with a total of 7.8 GW(e) in Taiwan), and 24 reactors are either under construction or have received state approval for an additional 24 GW(e) capacity.

A number of nuclear power development goals have been examined and set by the central government. Since 2005, the officially released and approved mid to long term nuclear power capacity goal has been set to 40 GW(e) installed with 18 GW(e) under construction by 2020. However, the recent adjustment will almost certainly far exceed that capacity goal. In fact, as a medium growth scenario, it is likely that the new goal will be 70 GW(e) installed by 2020, with 30 GW(e) under construction. Assuming a total installed electric generation capacity of 1500 GW(e), the nuclear capacity share will be 4.6% and the nuclear electricity production share will be about 7 to 8%.

Under this scenario, the nuclear capacity should reach 200 GW(e) by 2030, with a capacity share of 10% and a production share of 15%. The corresponding numbers shall be 400 GW(e), 16% and 22% by 2050.

The mainstay reactors in China are the so-called Generation II+, or improved Generation II PWRs. The majority of them are CPR-1000. More advanced Generation III or III+ reactors, such as AP-1000 or EPR, are being constructed on a limited basis. If the first four AP-1000 reactors are successfully constructed with good records and performance, then AP-1000 and its derivatives will become the main types of reactors for future deployment, especially for inland sites.

The increased exploration for uranium has led to increased known reserves, which appears to provide sufficient nuclear fuel for mid term nuclear power growth with supplements from foreign sources.

The second step, the development and deployment of fast reactors and the associated fuel cycles, is at the threshold of moving from a limited experimental phase into large scale development and commercial demonstration. China plans to transition into a fast reactor regime during the years 2020–2030 and begin making fast reactors the main reactor type after 2035. The China Experimental Fast Reactor (CEFR) is expected to go critical in the near future and commercial demonstration of fast reactors is also being explored with the BN-800 reactor as a potential candidate.

China plans to close the nuclear fuel cycle with reprocessing, and is exploring options in commercial reprocessing facilities and launching large scale R&D to support the closed fuel cycle strategy. The approach to long term waste management under consideration and development is the use of a geological repository. An underground laboratory will be built by 2020.

There are, however, other types of advanced reactors under development. Most notable are the pebble bed modular reactors or high temperature gas cooled reactors. The construction of 2 modules for commercialization demonstration has started. These reactors are being developed and demonstrated for other applications such as hydrogen production and process heat.

IX–2. NUCLEAR ENERGY DEVELOPMENT SCENARIOS IN INDIA

Overview and general policy

The logical evolution of the Indian nuclear power programme, along with its growth profile, is brought out in a paper written in the year 2004. This reference does not reflect the changes (increase) following the opening up of the Indian market for the supply of additional LWRs and uranium fuel. The currently considered characteristics of the reactors and their fuel cycles are described in the following.

The supply of uranium (yellow cake, or enriched uranium + tailings) for the LWRs would be drawn from imports. All the reprocessing capacity needed for the Indian programme will be located in India. All the enrichment capacity needed for the Indian programme will also be located in India beyond about the year 2025. In addition, India will position itself to provide fuel cycle services to meet the needs of some other countries [IX–1].

The suggestions given below are meant for the purpose of ongoing studies within the INPRO project, to facilitate general conformity with the projected size and composition of the Indian nuclear programme, taking into account the fuel cycle related policy mentioned above.

Scenarios

For the purpose of the current study, which is indicative in nature, it may be adequate to take the data presented in the above-mentioned paper as a moderate scenario.

For the low scenario the implementation of light water reactors (LWRs) and start of fast neutron reactors (FBRs) should be delayed by 5 years.

For the high scenario the number of LWRs should be increased from 8 to 40, and their reprocessed Pu should be used to add to the FBR capacity. The recycled uranium obtained from reprocessed LWR spent nuclear fuel should be used to fuel pressurized heavy water reactors (PHWRs), and the spent nuclear fuel of these PHWRs should be used to fuel additional FBRs.

Beyond 2052 the growth of the installed capacity will continue to rapidly reach at least 50% of total electricity supply, and thereafter at a moderate rate. Thorium will be brought in FBRs and molten salt reactors (MSRs) as necessary to support the growth. The high temperature reactors (HTRs) will be added to progressively enhance the contribution of hydrogen to meet the need arising from deficiency of fluid fossil fuels.

REFERENCE TO ANNEX IX

[IX–1] GROVER, R.B., CHANDRA, S., Energy Policy **34** (2006) 2834–2847.

Annex X

A VISION OF NUCLEAR ENERGY AND ASSOCIATED WASTE MANAGEMENT BENEFITS

Matching the objectives of a sustainable energy supply in the future for the world will, at least, demand continued use of nuclear energy and potentially even a significant expansion of the use of nuclear energy throughout the world. Today's nuclear power fleet only serves 6.5% of the world's primary energy demand but climate change and a further deployment of electricity as networked energy carrier could add a higher demand on nuclear energy.

Questions that arise in the context of such a wider spread use of nuclear energy are, among others:

- Are sufficient fissile and fertile materials available to sustain such growing nuclear energy use?
- What is the optimal use of such fissile and fertile materials considering the different nuclear power park deployment strategies that may occur and given socio-political constraints such as non-proliferation?
- Do today's larger size nuclear power plants fit all future needs or shall there be a need for a larger range of nuclear power plant sizes and how would these impact the nuclear fuel cycle needs?
- How can sustainability from a resource and waste management perspective be achieved in an increasingly liberalized energy market environment?
- How can sociopolitical concerns, especially on non-proliferation, be adequately addressed given a worldwide spread of nuclear power plants and thus nuclear fuel use?

Figure X–1 introduces a so-called 'millennium' look on nuclear energy, i.e. schematically showing the possible main strategies ahead for nuclear energy irrespective of the timing when these would be deployed. The figure provides essentially a look into resource sustainability of the world inventory of fissile and fertile materials as function of the cumulative nuclear energy generated (i.e. time is hereby a derivative depending on what the future energy market might demand as nuclear energy supply).

Figure X–1 shows that during the first 50 years of nuclear energy use, natural uranium (U_{nat}) resources became depleted as the deployed nuclear reactors were mostly based on thermal reactor technology needing enriched uranium fuel. The use of U_{nat}, and the subsequent enrichment to ^{235}U fuel for thermal (light-water) reactors

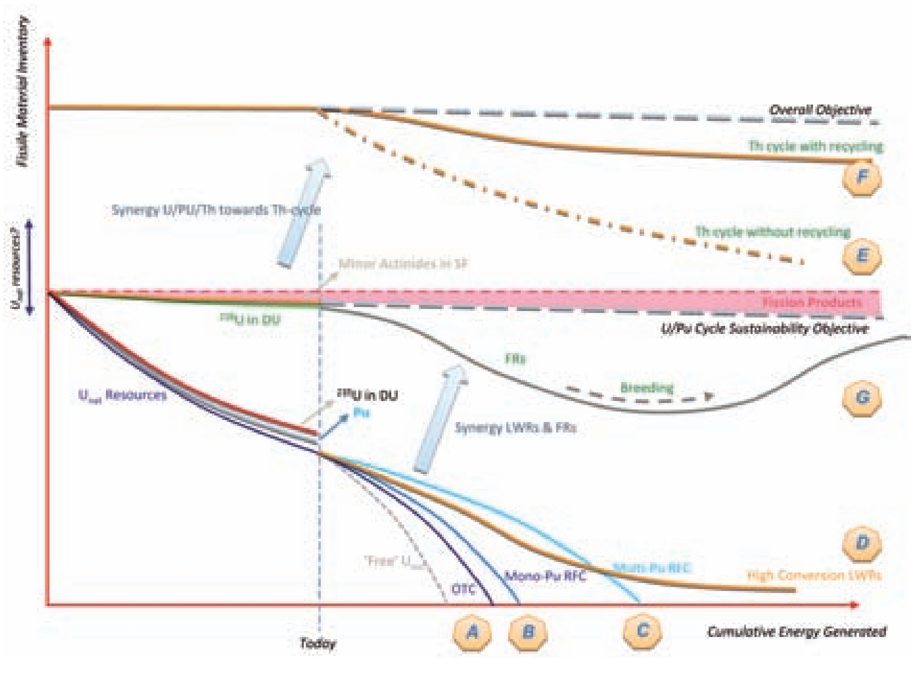

FIG. X–1. Schematic representation of nuclear energy's past and challenges for the future from a resource perspective.

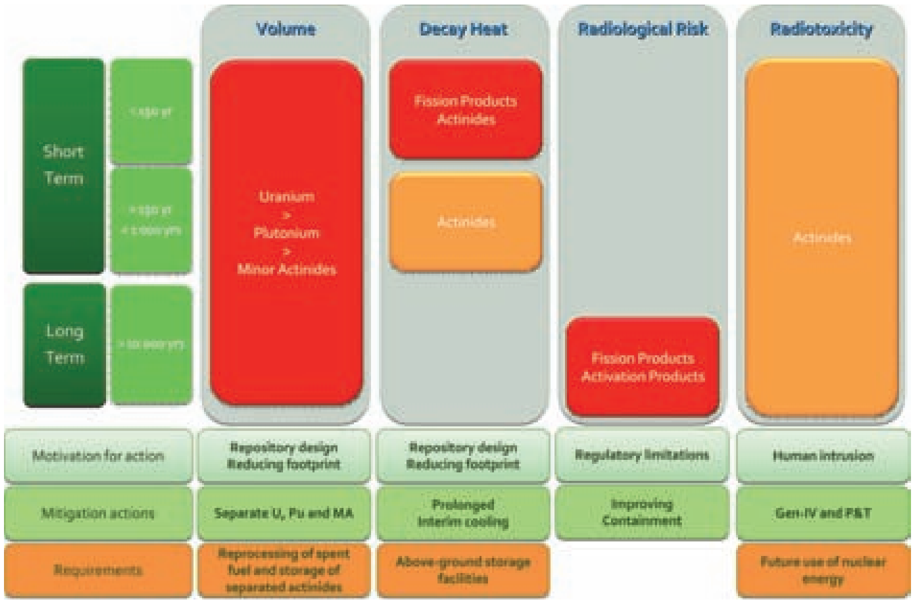

FIG. X–2. 'Key' drivers in radioactive waste disposal design and performance.

resulted in an increasing amount of depleted uranium (DU), with some 0.3% ^{235}U on average, and also an increasing inventory of spent fuel still containing a lot of fissile material, i.e. enriched uranium (typically from LWRs still containing around 0.8% ^{235}U) and plutonium, and also minor actinides and fission products.

Multiple fissile material stocks is the inevitable outcome from the use of U_{nat} and light-water reactor technology. Such reactor technology needs low fissile working inventories (compared to fast reactors as discussed later) and, in an initial phase of a nuclear programme deployment, is very useful to deploy without overly demanding advanced fuel cycle technology or high initial working inventories of fissile material. However, the deployment of this thermal reactor technology, in parallel to changes in the energy market and societal changes, has led to certain impediments that nuclear energy has to face today.

The growing amount of spent fuel due to imbalance between spent fuel generation and spent fuel disposal has provoked societal debate on the future of nuclear energy and the need for long-term waste management. From a scientific perspective, such spent fuel cannot be considered as waste due to the large amount — typically more than 94% — of fertile and fissile material that it still contains. Only the fission products are to be considered as ultimate waste in amounts directly proportional to the amounts of nuclear energy generated (see also Fig. X–1, the fission product fraction being proportional to the nuclear energy generated). To address this public concern about waste management, both fission product and actinide management approaches can be deployed. An overview of 'key' drivers and incentives for action on such actinide/fission product management are shown in Figure X–2.

The main issue in the societal discussion on the acceptance of technically mature and sound long term waste management approaches for such nuclear waste relates to the long term aspect, i.e. the requested assurance and especially the societal acceptance that a long term waste management solution is perceived best practice.

The radiological risk of such nuclear waste is primarily defined by some long lived mobile fission products and to a much lesser extent by non-mobile actinides (some exceptions for Yucca Mountain where ^{237}Np may also be important). The radio-toxicity of the waste is more governed by the actinides contained in the waste.

Reduction of the amount or size (or footprint) of a nuclear waste repository demands reduction of the thermal load of disposed waste. This thermal load is governed by the fission products (FPs) for the first 150 years and afterwards by the actinides. Reducing the thermal load thus involves three possible avenues (any combination of these can be envisaged):

(1) Longer cooling of the waste before disposal results in a reduction of the decay heat of the fission products;
(2) Separation of the most heat emitting isotopes in waste, i.e. essentially fission products such as ^{90}Sr and Cs, with storage of these separated fission products until sufficiently decayed;

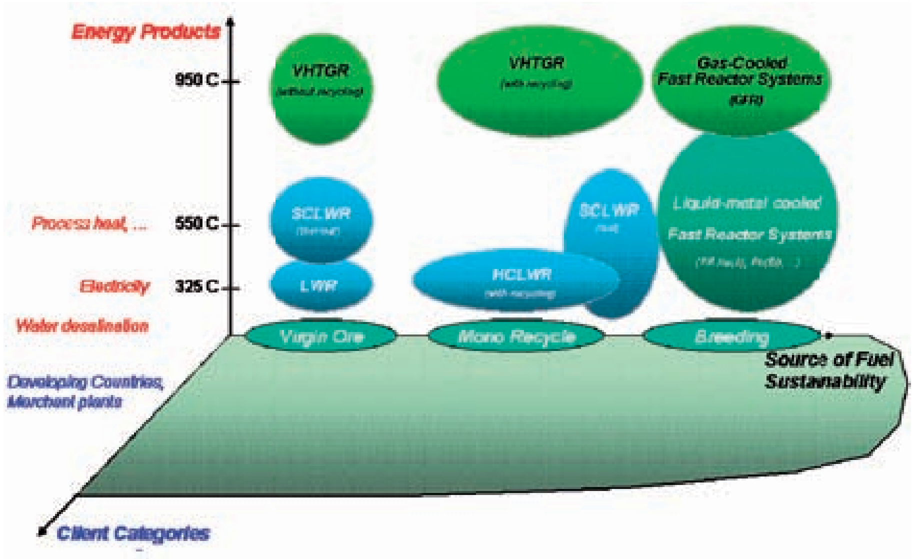

FIG. X–3. The three dimensional grid for future nuclear energy system deployment.

(3) Reduction of the amount of actinides contained in the disposed waste. Longer term cooling is a possibility to reduce the decay heat from curium (though this does not alter the radio-toxicity of the disposed actinides).

The amount of SNF to be deposited can be reduced by reprocessing the SNF and thus leading into various streams of separated actinides and fission products. Today, the PUREX process has been used commercially, resulting in separated uranium, plutonium and a combined minor actinide and fission product stream. The minor actinides and FPs are then embedded in a glass matrix as a final waste form for disposal.

Societal issues may arise with respect to non-proliferation of fissile materials when there is an imbalance between the separated Pu stream and the re-use of this Pu in nuclear reactors. Although no diversion of any separated fissile material from commercial fuel cycle facilities, including reprocessing plants, has taken place, nuclear energy deployment in the future, as it did until now, will have to take account of addressing non-proliferation of this separated fissile material and especially in providing an answer to the perception that such more widespread reprocessing would go hand-in-hand with an increased risk for proliferation.

Today, in light of the prospects of an increasing use of nuclear energy worldwide, there are also increasing concerns about the resource sustainability of nuclear energy, i.e. essentially the question if there is enough U_{nat} available in time to feed this growing nuclear energy park worldwide?

The past 50 years have not only resulted in a depletion of the available U_{nat} resources but, also shifted the fissile/fertile material balance in two ways:

(1) *A value-shift*: U_{nat}, as mentioned before, gets transformed into depleted uranium (DU) and finally also in SNF. This depleted uranium, i.e. for more than 99.5% ^{238}U, is not directly useful in thermal reactors but becomes so in fast spectrum reactors (FRs) given that the fertile ^{238}U then becomes transformed into fissile ^{239}Pu. DU may then represent a very large energy resource for the future though needing the deployment of such fast reactors to be used at its full potential.

(2) *A geographic shift*: U_{nat} mines are essentially found in countries around the world (see Fig. X–3) with no or relatively little use of nuclear energy where this mined U_{nat} gets transported and used in nuclear developed countries. As such, a geographic shift takes place from U_{nat} mines into '^{238}U mines' (i.e. DU).

Figure X–3 shows a three dimensional representation of the option space one has in developing nuclear energy in the future, addressing reactor technology, fuel cycle technology and energy market constraints, i.e.:

— A variety of reactors can be considered serving various energy product markets;
— The fuel for such reactors can be derived from virgin natural U resources or increasingly from the recycling of separated fissile/fertile materials from spent nuclear fuel containing U or Th;
— Various countries and regions will have different energy market situations, demanding a variety of small and large nuclear power plants with, for sociopolitical reasons, certain preferences to receive nuclear fuel via various paths though global assurance compliance with non-proliferation legal instruments.

The 'free' available U_{nat}, i.e. not yet contracted to operational or scheduled reactors, shall decrease faster than the physical U_{nat} resource possibly leading to increasing U_{nat}-prices due to trading phenomena and longer term front end service contractual arrangements requested by utilities to guarantee delivery of such services. Today's projections (even on the low side) of nuclear energy deployment during this century, and assuming today's estimates of U_{nat} resources ranging between 5 (known conventional resources) and 20 million tones of U_{nat} (known and undiscovered resources) with production costs lower than US \$130 /kg could result in a depletion of these resources towards the end of this century, and especially a depletion of the 'free' available U_{nat} earlier. Combined with an increasing average technical lifetime of nuclear power plants, in the future even well beyond 60 years lifetime, any investor in such new nuclear power plants will demand assurance of fuel supply during at least a significant part of its asset technical lifetime and shall also increasingly focus on fuel cycle flexibility allowing to hedge against any future fuel cycle market challenges (such as price increases, price volatility, perceived shortage, etc.).

Referring again to Fig. X–1, the main objective for a resource sustainability of nuclear energy is to increase the 'world nuclear energy system conversion ratio', i.e. the ratio of net fissile material creation to fissile material used in the nuclear energy system.

Today's LWR technology has a conversion ratio ranging around 0.6. Use of MOX-fuel (see scenario B in Fig. X–1) allows increasing the conversion ratio of the nuclear energy system a little, resulting in a saving of up to 20% of U_{nat} when combined with the recycle of the separated uranium. Multiple recycling of Pu, i.e. multiple MOX generations, is limited in today's LWRs to about 3 recycles (see scenario C in Fig. X–1) and, due to the needed changes in fuel cycle facilities not envisaged for the immediate future. Anyhow, the nuclear energy system's conversion ratio increases through use of MOX, though the reactor's conversion ratio as such doesn't.

Higher conversion ratios in LWRs is possible through use of so-called high conversion ratio LWR designs resulting in conversion ratios towards 0.8–0.9 and in very advanced designs even reaching 1 (or even very slightly above 1). Though the only (but welcome) effect such high conversion ratio LWR technology would have on the resource depletion as shown in Fig. X–1 would be that, with a conversion ratio of 1, the depletion of U_{nat} would become flatter. Ideally, with a conversion ratio of 1 the slope as shown by scenario D in Fig. X–1 would be reached, i.e. the slope of the 'U/Pu cycle sustainability objective' where only fission products are 'lost' but where the ^{235}U becomes replaced by new fissile material. Nevertheless, in such a case there is still a need for U_{nat} mining obviously to provide working inventory for new nuclear power plants and, in reality as the conversion ratio of the nuclear energy system or such high conversion LWRs as a whole would remain below 1, to provide top-up fissile material (also given that the Pu isotopic vector in such scenario degrades rendering it less/not useful in such LWRs).

Any thermal neutron reactor based scenario is essentially based on $^{235}U/^{239}Pu$ use of fissile material with very limited use of a continuously growing new 'mine' of fertile material, i.e. the ^{238}U in the DU inventory. Full use of this ^{238}U demands the introduction of fast spectrum reactors (scenario G in Fig. X–1) allowing to more efficiently transform the ^{238}U into fissile ^{239}Pu and making virtually full use of the energy content of the U_{nat}.

The main difference between FRs and thermal reactor technology is that FRs may indeed curb the depletion curve and trend towards the ultimate U/Pu cycle sustainability objective, i.e. only producing (losing) fission products as ultimate waste.

The technically achievable maximal conversion ratio of FRs is around 1.5 to 1.6, demanding use of advanced FR designs with metal fuels and short cooling times (and thus small working inventories of fissile/fertile materials in the fuel cycle). Any self sustained growth of a FR park is limited due to this upper limit of achievable conversion ratio (called breeding ratio in this case of conversion ratios >1). Any growth beyond would demand other technologies such as fusion neutron sources or accelerator driven systems introducing exogenously generated neutrons to transform fertile material into fissile material.

In addition to the use of U/Pu, use of thorium can be considered for a variety of reasons based on some inherent advantages of the ^{232}Th/^{233}U fuel cycle, i.e.:

- Th is estimated to be more abundant than uranium resources though technical and economic conditions may limit the exploitable amount.
- Use of ^{232}Th/^{233}U allows higher conversion ratios in thermal neutron reactors as LWRs. Combined with a higher conversion ratio core design of LWRs, this may more easily maximize the overall conversion ratio of a LWR based nuclear energy system.
- However, any use of the ^{232}Th/^{233}U demands a transition in synergy with the U/Pu cycle as medium/high enriched uranium or plutonium is needed as fissile materials to initiate the ^{232}Th/^{233}U cycle.
- On the basis of the previous description, there are three main families of scenarios for future deployment of nuclear energy (see Fig. X–1), i.e.
- The ‘thermal’ route based on thermal neutron reactors continues to use the U/Pu fuel cycle with a further depletion of the U_{nat} resources. Scenarios A through D in Fig. X–1 represent typical cases differing in reactor and/or fuel cycle technology being deployed. This scenario family remains to use essentially only one part of the mined U_{nat}, i.e. ^{235}U (obviously, during irradiation of fuel in reactors, ^{238}U captures neutrons becoming ^{239}Pu which fissions as well and contributes about one third to the energy generated in thermal neutron reactors).
- The synergistic thermal and fast neutron reactor both use the ^{235}U and ^{238}U from U_{nat} are used in thermal and fast reactors and this according to a variety of scenarios using to varying degrees the possible synergies between these reactors to varying degrees (Scenario G in combination with A to D in Fig. X–1).
- Deployment of the thorium fuel cycle extending further the available natural fertile/fissile material base (Scenario E and F in Fig. X–1).

In the very long term, fusion neutron sources and/or accelerator driven systems (ADS) as additional fissile material breeders may be considered encompassing the limitations of a maximum breeding ratio of around 1.6 in FRs.

Do we need all these technological options for a future sustainable nuclear energy system? The easy answer is ‘yes’ for a variety of reasons.

Nuclear energy deployment will be different in various regions around the world, i.e. due to technological capabilities, due to proliferation concerns, due to economic energy market conditions and many others, i.e. we cannot assume that nuclear energy systems will be similar worldwide. In fact, facing the possible rapid growth of nuclear power in currently developing countries where initially LWR technology would be the major contributor to nuclear park deployment, the world as a whole will be essentially trending on the scenario A curve in Fig. X–1, i.e. resulting, possibly, in a rapid depletion of U_{nat} resources.

From a sustainability perspective for nuclear energy, those countries having the financial and technological capability to deploy ‘advanced’ nuclear energy systems therefore should (need to) compensate this scenario A trend with other (at least scenario B), scenarios resulting in a worldwide increase of conversion ratio.

Utilities will increasingly demand assurance of fuel supply and on fuel cycle flexibility with the latter, next to operational flexibility by fuel cycle facilities, essentially demanding the availability of various fissile material sources and thus relying on recycling of those fissile materials. Though, providing these various fuels based on various sources of fissile material essentially is a fuel cycle decision matched with nuclear energy system deployment in the future.

Not all energy markets will be able to accommodate large nuclear power plants and small to medium sized nuclear power plants may become increasingly requested though also having an impact on the nuclear fuel cycle which, if no changes are implied, would result in a higher frequency of transports of fresh and spent nuclear fuel around the world. Other options to address these concerns are therefore adequately researched.

ABBREVIATIONS

DESAE	Dynamics of Energy System of Atomic Energy (analysis methodology)
DU	depleted uranium
EPRI	Electric Power Research Institute
FBR	fast breeder reactor
FINITE	Fuel Cycles for Innovative Nuclear Systems through Integration of Technologies (INPRO collaborative project)
GAINS	Global Architecture of Innovative Nuclear Energy Systems (INPRO collaborative project)
HTR	high temperature reactor
JRC	Joint Research Centre of the European Commission
IPCC	Intergovernmental Panel on Climate Change
IPPE	Institute for Physics and Power Engineering, Russia
LWR	light water reactor
PWR	pressurized water reactor
RDIPE	Research and Development Institute on Power Engineering
SMRs	small and medium (thermal) reactors
SNF	spent nuclear fuel
SRES	Special Report on Emission Scenarios (developed by IIASA)
VUJE	Výskumný ústav jadrových elektrární, Slovakia
WCR	water cooled reactor

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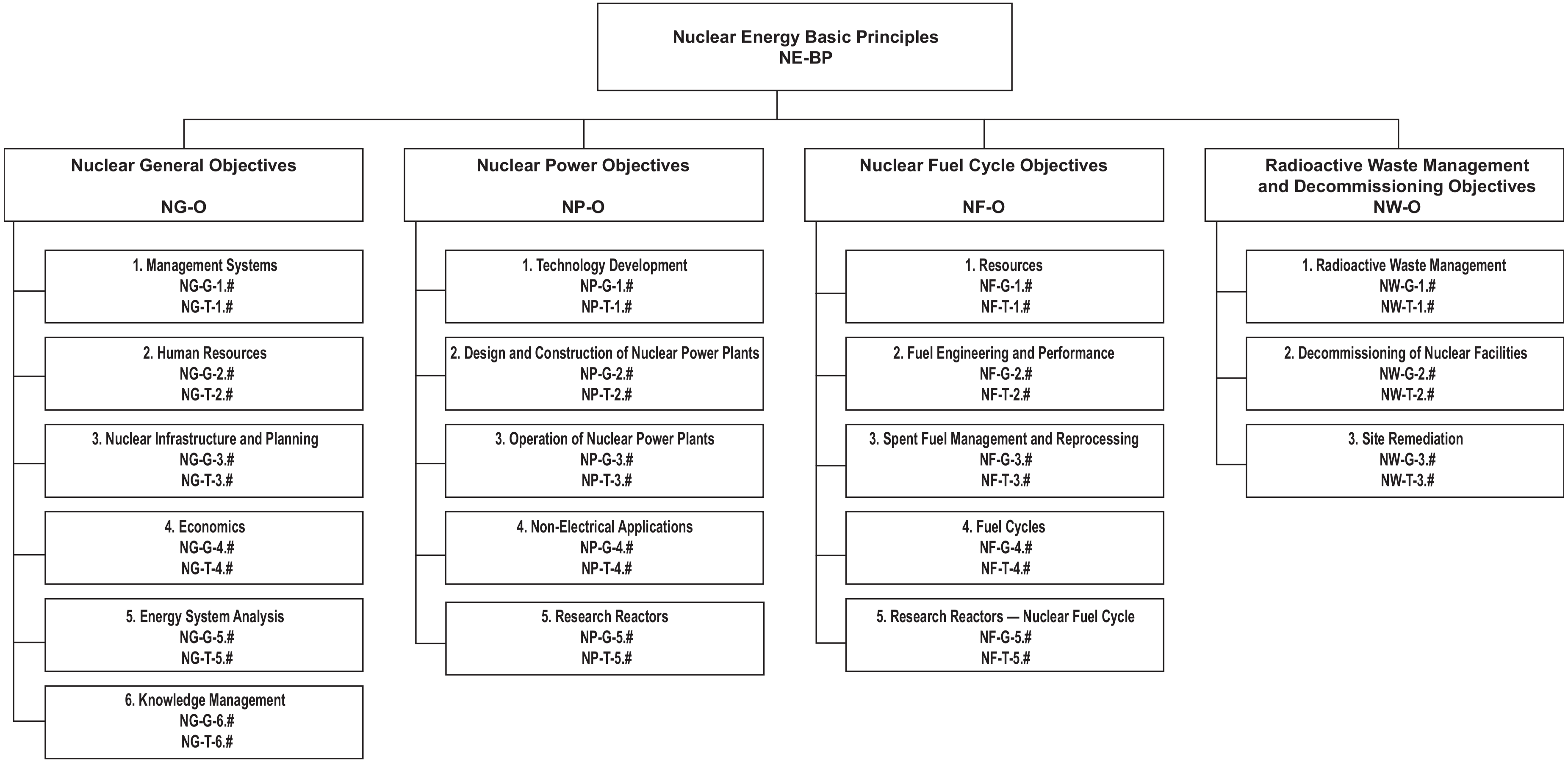

Key

BP: Basic Principles
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