

INPRO Study on Opportunities and Challenges of Large-Scale Nuclear Energy Development

S.Subbotin^{*}, M. Khoroshev^{**}

^{*} *Russian Research Centre “Kurchatov institute”*

Tel: +7-495-1969417, e-mail: Subbotin@dhtp.kiae.ru

^{**} *International Atomic Energy Agency (IAEA)*

Wagramerstrasse 5, P.O.Box 100, A-1400 Vienna, Austria

Tel: +43-1-260026716, Fax: +43-1-260029598, e-mail: M.Khoroshev@iaea.org

INTRODUCTION

The IAEA International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) can be considered as the IAEA's response to the challenges of growing energy demand. INPRO's activities are intended to help to achieve one of the main objectives of the IAEA - to promote the development and peaceful use of nuclear energy. INPRO applies a carefully developed Methodology to assess Innovative Nuclear Energy Systems (INS) and to define R&D needs and deployment strategies for the development of large-scale regional and global INS. The purpose is to match the opportunities and challenges of sustainable energy supply provided by nuclear energy (NE) to the global balance of demands and resources.

In order to make the most of the opportunities and face the challenges of nuclear energy (NE) in the event of its renaissance, IAEA Member States need to consider its large-scale development. INPRO proposes a global vision, which can provide justified guidelines for this development. Consequently global

system analysis is needed for three reasons:

- To estimate the contribution of NE towards achieving sustainable development at a global level;
- To understand the boundary conditions for NE development (such as global energy demand, economic data, available resources, environmental issues, non-proliferation, safety, etc.);
- To identify effective institutional and technological development responses which will have a global impact.

One of INPRO's activities is “Determination of national, regional and global balances of demands and resources”. A preliminary study of the opportunities and challenges of NE has been performed. It concluded that the opportunities and challenges of large-scale NE development, presented by the global balance of demands and resources, require concrete and timely actions to be undertaken by interested stakeholders in order to address the emerging need of large-scale nuclear energy development.

Currently energy suppliers, other than nuclear, consider NE as a competing energy technology. But in 10 years we expect NE to be viewed as the necessary stabilizing factor for sustainable development of the whole power sector. In this case NE will have to demonstrate its capability to serve as a key factor in this regard.

The paper presents the main results of the study on analysis of global energy demands and resources, and proposes some innovative approaches, which could be undertaken, using INPRO's experience, to meet the challenges of large-scale nuclear energy development.

DESCRIPRION OF THE ACTUAL WORK

Short-term and long-term forecasts

Short-term forecasts of power development include plans intended for implementation in the near future. They are normally based on political decision, economic optimisation (minimization of expenses and maximization of profit) and assumptions that economic, political and environmental conditions will remain constant. However past experience shows that these conditions change, and so the "business-as-usual" approach results in forecasts that are not always very accurate.

- Until now, management based on market considerations have proved to be stable and viable, enabling profits to be maximized. This was possible as long as the availability of resources was not restricted. And the primary concern was just to identify and exploit them.

- Development in such conditions can be very rapid but can be sustained only while resources are viewed as unlimited. Costs involved include exploration, production, processing and consumption. Environmental damage is not taken into account and is left for future generations to deal with.
- Thus the market mechanism can work only under the following conditions: when there are no restrictions due to depletion of resources; and when man's influence on the environment is minimal.

However, all known estimates of resources, in particular of fossil fuels, do not fit these conditions. The mechanism which has allowed human society to develop under conditions which would be impossible as part of any long-term plan, will fail in 21st century. Other forms of management will have to be found.

Long-term forecasts are usually base on assumptions of practically constant economic, political, and environmental conditions (business as usual) or, occasionally, taking into account some changes identified with the help of feedback from earlier forecasts. But long-term forecasts are not plans and there is no fulfilment requirement. They aim to create a possible picture of the future as envisaged by those with certain expectations seeking either to facilitate desirable consequences, or to avoid or mitigate undesirable consequences.

It is impossible to predict the scale, structure, timeframe or conditions of power development for the whole century, especially using business-as-usual assumptions. Therefore it is more reasonable to consider various more "fundamental" parameters, which will

strongly influence power development. These include:

- The rate of population growth;
- The population's changing needs;
- The availability of resources;
- Various trends, requirements and restrictions of a political, economic, psychological or ecological character, which may vary over a century.

While short-term forecasts can consider power separately, long-term forecasts cannot afford to do this. .

Global resources

There are two types of resources: renewable and non-renewable. Society can be sustainable, if:

- The rate of consumption of renewable resources does not exceed the rate of their renewal;
- The rate of consumption of non-renewable resources does not exceed the rate of development of their steady sustainable replacement;
- The amount of polluting substances released do not exceed of the ability of the environment to assimilate them.

The role of non-renewable resources in the functioning of modern society is extremely important. Stocks of fossil and nuclear fuel are sufficient for the 21st century. But taking into account at the level of production, delivery and consumption of power resources, and the labour costs of producing fuels in increasingly remote regions, it is clear that peak production of petroleum, gas, coal will be achieved in the first half of this century. In the second half it will be necessary to rely on nuclear energy and renewable sources. It will be necessary to limit not only the

integrated use of fossil fuel, but also the maximum capacity of power production and consumption as well as the local production and consumption of energy.

Global demands

Population

Estimates of the world's population at the end of the century range from 8 to 25 billion. Practically all estimates assume stabilization by the end of the century, and some forecast a peak in the middle of the century followed by a reduction caused by adverse changes in the environment and declining food production.

Of greatest concern is the fact that energy consumption growth is linked with population growth, which is expected in the countries of Africa, Asia, Latin America, where the use of commercial power resources is not properly developed. It is therefore difficult to predict future needs.

It is notable that the most complex models used for estimations of population growth, which include more feedback predict smaller population growth, and this is directly related to needs.

Needs

The size and the structure of modern and expected energy consumption per head in various countries are shown in Fig. 1. Currently about 6% of the world's population use less than 3 GJ (0,1 t.c.e.) of energy per head in a year. Such consumption has ensured survival in zones with a warm climate for 10,000 to 12,000 years. About 15% of the population now spend 5-6 GJ (0,18-0,21 t.c.e.) per head in a year. This has been enough to ensure survival for millennia in zones with a moderate climate.

European civilization was not content with this level of energy consumption, and over the past 6-8 centuries a technological society developed which learned to use both renewable, and non-renewable power resources. The use of industrial power has since spread to other continents. Now average world energy consumption per head exceeds basic needs in food, clothing, habitation and transport almost tenfold.

Since 1985 the average energy consumption per head in the world has stabilised at a level 2.3-2.4 t.c.e. per year. And by the middle of the next century average energy consumption per head is predicted at 2.4-2.5 t.c.e. a

year. So the world is not expected to go the way of the USA, which consumes 11-12 t.c.e. per head per year. However, this is not a deliberate or conscious restriction of consumption, but a simple reflection of a level of technical and economic opportunities available. Mankind will not return to former "steady" energy consumption level, and needs to find not only power resources to satisfy present day requirements but also to ensure an ecological balance. The present-day level of energy consumption will certainly destroy this balance. If man continues to use up natural resources without any thought to the future.

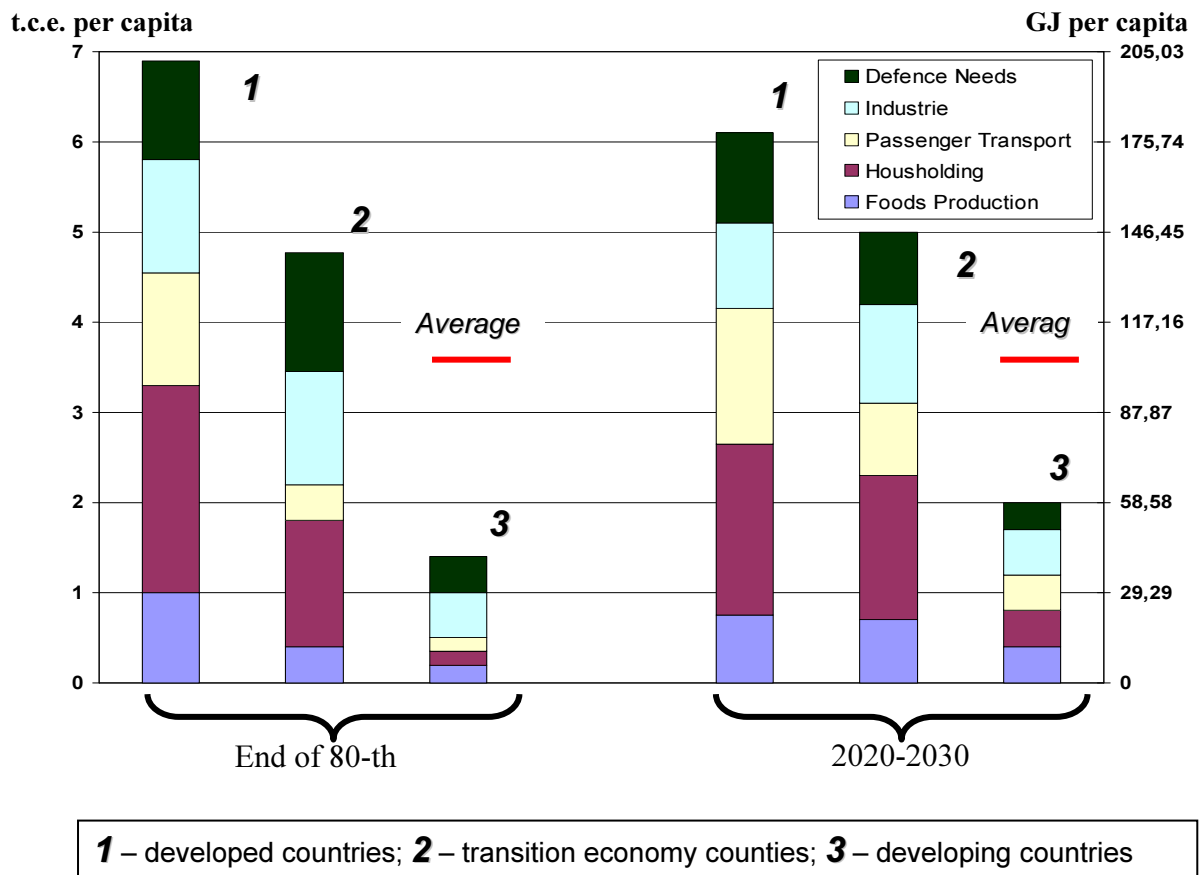


Fig.1 Size and structure of per capita energy consumption

Reference energy scenarios considered in INPRO

The choice of the input parameters for the global nuclear energy system model should be based on dynamic projections of world energy consumption, determined by demographic growth and the rate of the global and regional economic development. These projections are based on the results of a study carried out by a large group international of experts, which developed “emission scenarios” (SRES), the results of which were published in 2000. This group prepared, under the auspices of the Intergovernmental Panel on Climate Change (IPCC), 40 scenarios (divided into four major groups) looking at demographic growth, economy and energy demand development rates, as well as energy resources and their production [4]. Some parameters of the four groups of the IPCC economy and power development scenarios, together with the assessment of A2 and B2¹ scenarios are assumed as basic in the following considerations.

The scenarios mainly differ according to economy growth rates (A1 and B1 – high rate; A2 and B2 – low rate) and development trends (A1 – material indicators’ growth, or B1 –services and information prevailing); demographic growth rate (A2 and B2 – high, A1 and B1 – low); the rate of introducing new technologies (A1 – high); economic globalisation and liberalization rates (A1 and B1 – “homogeneous” world, A2 and B2 – “heterogeneous” world).

¹ It should be noted that the amount of nuclear energy produced in the world, according to these scenarios, makes about 6% of primary energy by 2050, and about 12% - by the end of the century, that corresponds to NPP capacity of 2000 GW and 5000 GW, respectively.

A2 scenario: Electricity is the only market for nuclear power products. NPPs do not produce hydrogen. The main capacity growth up to 2030 takes place in DDC, then in ALA and ACA. After 2030, these regions still dominate capacity growth, more or less equally. Most growth is in countries where there is no competition between fuel resources. Before 2030, coal (and to a lesser extent gas) is the main contender for new capacities. After 2030, the solar energy becomes the main competitor of nuclear. Nevertheless, in DDC and the FSU coal remains dominant until 2050-2060. In DDC nuclear power is expected to develop a little more rapidly than solar energy, while in Asia, after 2030, solar energy will develop much faster.

The A2 scenario places more emphasis on coal and assumes relatively moderate economic growth. It shows the long-term requirements related to the rapid exhaustion of gas and oil resources coupled with the slow progress in developing alternative energy sources. *In the initial SRES A2 scenario, nuclear technologies are used exclusively for electricity production, with growth from 45 EJ by 2050 to 130 EJ by 2100.* Coal technology is the main rival to nuclear under this scenario. In terms of power generation, nuclear is capable of providing an additional 30 EJ by 2050 and up to 90 EJ by 2100. As to non-electricity applications, nuclear could increase its district heating contribution with a growth factor of about 6 by 2100, which corresponds to additional heating of about 110 EJ.

B2 scenario: Nuclear power differs according to region, and plays a key role in Asia by 2050. The maximum growth in NPP capacity between 2040 and 2050 is in the developing

countries. . Electricity remains the main product of NPPs. B2 scenario describes the world in terms of “routine dynamics” and presumes moderate growth. It emphasises local rather than global, solutions, which results in heterogeneous development of the energy system. . Competition between energies differs from region to region depending on local circumstances, such as availability of resources and technology. *The original B2 scenario uses mainly nuclear electricity generation, with its contribution growing from 45 EJ in 2050 to 140 EJ by 2100.* However, electricity production could be increased by another 30 EJ by 2050 and 70 EJ by 2100. This could result in slower penetration of coal, natural gas and biomass in the Asian markets, and slower market penetration of solar energy globally. In addition to electricity generation, nuclear technologies could supply considerable amounts of process heat to produce synthetic fuels and improving the efficiency of fossil fuel use (10 EJ by 2050 and 40 EJ by 2100).

The B2 scenario was chosen as a reference scenario in several national and international assessment studies performed by INPRO members. In terms of GWe, the B2 scenario assumes that installed nuclear capacities will achieve 2000 GWe in 2050 and 5000 GWe by 2100.

Opportunities for nuclear technology

In the study, the B2 scenario was used as the basis for estimating possible options and challengers for INS development (IAEA-TECDOC-1362; 2050 – 2000 GWe, 2100 - 5000 GWe). One of the key factors determining the possible shape of the global nuclear energy system of the 21st century is the

current estimation of the world uranium resources.

The most widely used uranium resource estimations are contained in the Red Book periodically published by NEA/OECD, which summarises world data on uranium resources, production and demand. According to 2001 overview, the world’s known uranium resources total of 16.2 million metric tons of U. This includes Reasonable Assured Resources (RAR) and Estimated Assured Resources (EAR) at the highest price considered today of 130 USD/kg of U. It also includes additional resource estimates based on trends and “similarity” characteristics, “theoretical” resource estimates based on geological extrapolations, and, finally, resources identified in expert considerations as yet unclosed.

Inclusion of stockpiled resources – commercial reserves, military material, and possible depleted uranium enrichment – could increase the estimated amount of the world uranium resources to 17.1 million of metric tons.

However, criticism of this amount as an upper estimation such as that contained in the report of the Harvard University expert group – seems to be well grounded. The low level of the estimated resources is the consequence of insufficient financing of exploration, the lack of any incentives to look for uranium in price categories above 20-40 USD/kgU, the ongoing possibility of producing uranium as by-product of other resources, and some other considerations.

However, higher estimates of the uranium available for extraction at a cost of 130 USD/kgU and over are based either on qualitative considerations, or long-term

extrapolations of the correlation between cost and available resources, which is understood for prices below 40-50 USD/kgU. The use of amounts between 20 and 40 million tons for assessing nuclear energy in the context of the growth of uranium resources seems reasonable enough. But it requires more detailed consideration of the ecological factors involved, which could become important at such production rates.

None of these estimates takes into account the possibility of uranium extraction from seawater (about 4 billion tons), which could become feasible in future, as research continues to find acceptable technologies for uranium extraction from seawater.

It should be noted that thorium could provide a several-fold extension of the nuclear power fuel base – but this would require the creation of a thorium extraction, production and processing industry. Thorium, as a potential fuel resource, does not compete with uranium, but it could help to solve some nuclear energy problems. These include minimizing the amount of trans-uranium nuclides in the system, and extending the possibilities for using reactors with thermal and intermediate neutron spectra such as high-temperature heat and hydrogen co-generation reactors. However, during the period of rapidly growing nuclear power capacities, the large-scale introduction of thorium would hamper capacity growth, as nuclear fuel in a thorium-based system requires a much longer time than in fast reactor systems operating on uranium/plutonium fuel.

Use of LWRs in an open fuel cycle, in accordance with nuclear power capacity requirements under the B2 scenarios, would lead to high level of

natural uranium consumption. For example, if the system's capacity increases to ~ 2000 GW(e) by 2050, uranium extraction will have to increase to over 300,000 tons a year, and overall uranium consumption by 2050 could total over 10 million tons. By 2100, if the system's capacity increases up to 5000 GW(e), the annual uranium consumption would reach approximately 800,000 tons and a total uranium consumption over 40 million tons. The total amount of spent nuclear fuel (SNF) produced would exceed 3.5 million tons (requiring over 50 Yucca Mountain-type storage facilities)

Thus, a nuclear energy system with a once-through fuel cycle, even in the moderate scenarios, faces constraints related to estimated uranium resources. Development of uranium extraction and enrichment on such scale would require not only a more than tenfold expansion of the existing production capacities, but also the development of new technologies, to solve – among others – the environmental issues.

Closing the LWR fuel cycle by extracting plutonium (Pu) and loading it into fast reactors without breeding a breeding ratio of approximately 1.06) also provides no possibility of reaching the capacity levels proposed for nuclear under the B2 scenario (Fig. 2, 4). If about 16 million tons of natural uranium are used, the capacity of LWRs would reach about 1200 GW(e) by 2050, and then would fall to almost zero by 2100. Total INS capacity would reach its peak of 2100 GW(e) around 2060; fall to 1600 GW(e) by 2100 (assuming only plutonium fast reactors are introduced); and then would slowly start growing as a result of available excess plutonium produced in fast reactors (FR). After 2100 the extraction of natural uranium would stop completely. The maximum

uranium extraction of 200,000 tons a year would be reached by 2040, and the peak capacity of separation facilities (290 million SWU) would also be reached by 2040.

Introduction of FRs with plutonium breeding (a breeding ratio of around 1.6) in the nuclear energy system would make it possible to ensure the electricity production required by the B2 scenario, without exceeding the natural uranium extraction limit of 16 million tons (Fig. 6). Plutonium use in this case would start in 2020.

Challenges for large-scale nuclear power development

Global nuclear energy system model

Based on today's estimated uranium resource limitations, achieving nuclear power development as envisaged by the B2 scenario requires further consideration of the two-component structure of INS with Pu breeding. This clearly makes the search of additional uranium resources a necessary task.

These so-called "moderate" scenarios of the world nuclear energy development, which nevertheless allow growth up to about 10,000 GW by the end of the century including, for example, production of "nuclear hydrogen", assume conditions under which technological innovations can be implemented to solve the problem of uranium resource constraints. These innovations, which ensure improved fuel use, include the closed fuel cycle with a short reprocessing time, very good breeders (with BR ~ 1.6) and LWRs with a BR ~ 0.9 using uranium-plutonium fuel. However, it is difficult to imagine such a rapid rate of innovation without special

governmental (and intergovernmental) support.

Government decision-makers addressing this problem will have to take into account the inertia of nuclear technology development. Even in a critical energy resource situation, governmental decisions will be unable to make nuclear energy instantly provide and implement new technologies. Consequently, governmental institutions should ensure the advanced development of nuclear innovations. Rapid nuclear energy development will require not only the development and mastering of the INS innovations, but also the active search for additional uranium resources and development of new technologies for their extraction. Moreover, these two tasks are inextricably linked.

Reduction of the time fuel stays in the external fuel cycle is a very important target aimed at increasing the rate of large-scale nuclear energy development. In this connection, a cardinal innovative solution is offered by the introduction of liquid fuel reactors with continuous fuel processing (molten salt type). However, their large-scale deployment, in all probability, will extend beyond the 21 century, and will reach maximum efficiency when thorium is introduced as an efficient means of extending the NE fuel base. This would also reduce the environmental impact, and solve the issue of minor actinide disposal. Reduction of the external fuel cycle time in FRs from 4 to 1 years would make it possible to reduce the fuel load in the nuclear fuel cycle by about 15-25%, thus correspondingly increasing INS

development rates². Methods of increasing the energy density of breeder reactor cores in order to achieve the minimum doubling time have already been considered, but they obviously contradict current trends towards intrinsic safety features and passive means for improving reliability and safety of reactor operation.

Assumed parameters, which determine the rates of Pu breeding (BR ~ 1.6, external fuel cycle time – 3 years) makes it possible to assess the maximum realistic growth of the nuclear energy (in case of slight mitigation of uranium resource constraints – 10 million tons over the assessment adopted today). Under this condition, global nuclear power might reach 12 000 GWe (or about 300 EJ) by 2100. In this case, the nuclear energy system could generate (under the B2 scenarios) about 40% of electricity by 2050, and about 70% - by 2100³.

Estimates of the continued “delay in development” of nuclear energy to the mid-century show that, under this scenario, it would be also possible to achieve the 5000 GW lby the end of the century, but this would be possible only under very strict conditions of rapid deployment of breeders and an

additional “borrowing” of about 10 million tons of uranium.

In the same time, the “low” scenario doesn’t create any significant “innovation problems”, at least in the technology area. In the field of reactor technology development, the advancement of light-water reactors (including small and medium power reactors), as well as the broad introduction of high-temperature reactors for hydrogen production, would be enough. It should be noted that the range below this scenario (1000 GW by 2050) leaves nuclear energy as a “technological demonstration”, which would be an insurance against possible limitations in the development of other energy technologies.

If a closed nuclear fuel cycle (NFC) is used, and if INS use fast neutron reactors able to utilize efficiently over 70% of uranium, the energy potential of the nuclear industry becomes much higher than all the fossil fuel resources. The initial NFC stage is principally enhanced thanks to reduced uranium extraction, with a corresponding reduction of long-term risks – to several man·Sv per each GW·year of electricity produced. The SNF reprocessing option becomes more economically and politically realistic, even in case of using only thermal neutron reactors, because it requires considerably smaller resources to be spent for waste management in the long-term.

To put this in perspective, the issue of nuclear energy’s acceptability is connected more with confidence in organization and realization of the fuel cycle than with current capital investments in nuclear power plants.. This would guarantee large-scale and long-term development without steady

² Probably, it would be expedient to consider – as a means of reducing the nuclear fuel load in the NFC – SNF reprocessing at NPP sites with high-capacity fast reactors (impact of such technologies on non-proliferation regime requires a separate discussion). But this way would be efficient only in case of SNF unloading from reactor without its cooling in internal reactor storage facility, and in case the fuel reprocessing technology with high residual energy and radioactivity levels is created.

³ It should be noted that, in case of such nuclear energy development, fossil fuel extraction and carbon dioxide emissions could be stabilized on their present-day levels.

and growing resource and waste problems, which would contradict the Basic Principles and purposes of sustainable development.

SNF reprocessing and re-use of uranium and plutonium in reactors is a necessary condition for fuel breeding and for increasing the efficiency of uranium use by 10-20% in thermal reactors (and by an order of magnitude if fast reactors are used). Closing the fuel cycle also allows a significant reduction in high-level waste. Moreover, reducing americium, curium and neptunium (minor actinides) considerably lowers risks related to the long-term consequences of radioactive waste disposal. For an efficient solution in terms of sustainable development, the level of actinide reduction during reprocessing should be kept at about 0.1%. However, minor actinide transmutation – which requires additional reprocessing technologies, and complicates reactor construction, makes no sense, because it does not lead to any considerable reduction in long-term environmental risks. On the contrary, it considerably increases the current risk level by increasing the amounts of minor actinides in the reactors and NFC.

The introduction of liquid-fuel reactors for burning minor actinides (neptunium and americium and, after 2100, curium) and some other hazardous nuclides could be considered after 2050. But this is proposed just in case the problem of their safe and socially acceptable disposal (and, possibly, their partial use for the purposes not related to large-scale energy production) is not solved. This analysis does not take these reactors into consideration, but the acceptability of such a multi-component nuclear system could be considered from the sustainable

development viewpoint. This would require calculating the amount of radionuclides for all NFC stages. It would also need an assessment of the neutron efficiency of the nuclide composition of fuel in the system, radionuclide losses, and the capability of burning all hazardous radionuclides.

It should be noted that, despite the slightly different fuel components of various NFCs, fuel cycle structures and elements might vary considerably. That means that present-day economic assessments will not be suitable for fuel cycle selection. In the case of a closed NFC, it should be borne in mind that, over the next hundred years, the main problem could be represented not by high-level waste (its amount, risk level and energy rate is lower, than for SNF), but by low-level waste (LLW). The amount of LLW depends to a large extent on SNF reprocessing methods and the technological processes used. Not only may aqueous methods of SNF reprocessing require improvement, but also various non-aqueous methods of nuclide separation may be introduced to considerably reduce the volume of medium- and low-level waste. This could make nuclear energy attractive not only on the long term, but also in the near future.

Discussion view on priority areas of innovations in nuclear

The study concluded that innovations are needed for sustainable, large-scale and long-term energy development. Priority areas for innovations in nuclear can be specified by modelling various global energy development options. These innovations should be viewed as a basis for sustainable development this century.

Innovations could include the following:

The development of efficient breeders on the basis of fast spectrum neutron reactors:

- at the initial stage, specific loading of plutonium into the reactor to a minimum (up to 3–4 t per GWe), breeding ratio of 1.2–1.3; duration of the external fuel cycle for plutonium would be no more than 5–6 years;
- after 15–20 years, the plutonium breeding level in a fast reactor would have to be raised to 1.5–1.6; duration of the external fuel cycle for plutonium would be no more than 3 years

More efficient fuel utilization in thermal neutron reactors (breeding ratio 0.9) through:

- closure of the plutonium fuel cycle;
- improved reactor core design;
- transition to a uranium-thorium fuel cycle, particularly for high-temperature reactors.

The development of non-aqueous methods of reprocessing spent nuclear fuel for:

- shortening of external fuel cycle;
- reduction of waste.

This will lead to:

- a reduction in the amount of fuel in the nuclear energy system;
- a positive impact on the resolution of problems including:

- non-proliferation;
- ecological acceptability;
- fuel utilization;
- and reducing the share of fast reactors in the system.

The development of liquid fuel reactor-waste incinerators (burners of minor actinides) to close the nuclear fuel cycle for minor actinides, which will significantly ease the problems of:

- disposal and minimization of the quantities of hazardous nuclides in the nuclear energy system;
- non-proliferation;
- ecological acceptability;
- effective utilization of the neutron potential of nuclear fuel.

Development of low-power capacity reactors to provide high-quality reliable energy supply services in regions of the world where normal, efficient economic activity would be impossible without them.

These nuclear power facilities should be transportable and with no need for any fuel and radioactive waste management procedures at their operating locations.

Development of nuclear energy technology complexes for the production of hydrogen and various chemical compounds based on its use, including the production of high-quality liquid fuels from low-quality fossil resources.

The total output of these nuclear power facilities will be **thousands of GW**.

To raise the energy conversion efficiency, these will most likely be thermal neutron spectrum nuclear power facilities (**ceramic structural materials**), and to improve their fuel utilization parameters a gradual **transition to thorium fuel** (more efficient in the thermal neutron spectrum than uranium-238) will be necessary.

Introducing thorium into the nuclear energy system will:

- decrease fuel loading in HTGRs;
- increase the thermal reactor share (up to 80%); and
- reduce the quantity of plutonium and minor actinides (by approximately a factor of ten per unit of power) in the nuclear energy system.

This will boost the requirements for neutron-efficient nuclide losses (uranium-233, plutonium-239 and 241, uranium-235) to 0.1%;

Development of methods for assessing neutron efficiency of nuclear energy systems

Efficient utilization of nuclear energy resources (uranium-238 and thorium-232) will be possible only if, for each uranium and thorium nucleus consumed, at least 0.3 neutrons will be obtained.

This indicator depends on:

- Reactor design (ranging from 0.25 for molten salt cooled reactors to 0.4 for transport nuclear power facilities with a high fuel burn-up);
- The time fuel is kept in the external fuel cycle

(decay of plutonium-241 and curium-244);

- Irretrievable losses of actinides during reprocessing (a reduction in plutonium loss from 1 to 0.1% would mean that the fast reactor share of the nuclear energy system could be reduced by a factor of roughly one and a half).

In the same way that economic requirements are derived from a “market mechanism” for seeking a price “consensus”, a **“humanitarian” process of “trade-off” should be established for reaching agreement between interested parties on key questions** including:

- Criteria for safety, non-proliferation, ecological damage;
- Necessary criteria for multi-variant analysis and the selection of acceptable options.

Scientists identify the dangers, evaluate them, provide information and give recommendations, but they do not take decisions on requirements and limitations.

Innovations in these areas will enable the **basic physical principles of sustainable nuclear energy development, as viewed by the authors**, to become a reality:

- The long-term risk will be proportional to nuclear energy capacity and not to overall energy output;
- The neutron efficiency of nuclear energy will increase;
- The lifetime of hazardous radio nuclides in

the system will become shorter;

- All the radio nuclides will be used efficiently, including utilization of all the extracted fuel;

Meeting user requirements does not guarantee conditions for nuclear energy development.

Innovative work on modelling the developing nuclear energy system is important for society, or at least for its responsible representatives, if they are to understand the need for nuclear energy development as a basis for sustainable development.

These models will help not only in selection of future areas for innovation, but also in structuring the emerging **nuclear energy systems** and in **developing a strategic vision for a sustainable energy supply**.

“There are many technical arguments, but the real solution is probably political. As the Rio conference demonstrated, very few World leaders are statesmen whose primary goals are long-term. Most are politicians whose goals are mainly short-term (to remain in power) though they are aware of long-term problems of mankind. In this paper it has been assumed that human nature is not going to change in a hundred years. The only effective way to find solutions to the World's energy problems is to make politicians aware that one of the conditions to achieve power, is to take action on solving long term energy and population problems”.

RESULTS

Decision makers, such as politicians, governments, non-

governmental organizations, investors and other active groups in society, could consider various aspects of nuclear energy's contribution to sustainable development. Such aspects should be raised in discussions on energy security issues, for example, at the forthcoming G8 Summit in St. Petersburg in July 2006. They include the following:

- Growing energy demands, the increasing impact of energy use on the environment and other issues of sustainability show there is a need of large-scale NE;
- One of the reasons why one fuel replaced another during history was that the new fuel was cheaper. In future, however, replacement fuel could be more expensive but with the compensation by major ecological advantages in reducing serious and obvious pollution. To enable the replacement of cheap fuel by a more environmentally acceptable one, external costs should be taken into account in the cost of the competing cheaper fuel;
- NE should be considered as part of the overall energy structure, including fossil energy and energy technologies based on natural processes (e.g. wind power, etc.);
- Current regulatory requirements for NE are high compared with other energy sources. This should be reconsidered. All energy sources should be assessed using a holistic methodology. The impact and role of different energy sources should be assessed. INPRO's methodology for the

assessment of innovative nuclear energy systems could become a starting point for development of such a holistic methodology for all energy sources;

- To ensure effective use of all energy sources, the international community should develop an appropriate energy policy, taking into account security of energy supply, as well as safety, environmental, social, political, economic and infrastructure issues. The experience gained through INPRO's INS assessment studies could facilitate the development of a new energy paradigm.
- It is necessary to implement innovations, which would facilitate deployment of large-scale nuclear energy, such as innovations in nuclear technology and in infrastructure.
- Innovations in nuclear technology would mean that INS would be needed to provide energy for sustainable development. Taking into account specific national and regional conditions, it is foreseen that different types of reactors and other facilities (with different functions in a closed nuclear fuel cycle), called components of INS, would be required to provide energy for a wide range of electrical and non-electrical applications. National/regional INS could be considered as components comprising a global INS, which would make it possible to change qualitatively the roles of different energy sources in the global energy mix (e.g.

hydrogen technology, clean oil-based motor fuel, etc.);

- Innovations in infrastructure would include, among other things, development of institutional measures, such as laws, norms, rules, regulations, etc. They would also include financial mechanisms, such as advanced insurance mechanisms, state's guarantees for long-term credits and tax reduction to facilitate gradual transfer of resources (intellectual, financial, human) from non-effective branches of fossil energy sources to innovative nuclear energy;
- International cooperation is vital for timely implementation of innovations, which would facilitate development and deployment of nuclear energy. International cooperation is urgently needed to perform the necessary R&D to develop in time different components of INS (including infrastructure) and, finally, to deploy INS as a large-scale energy source in the global energy mix.

Conclusions

The need for innovations in the energy sector in terms of their directions, terms, speed and scale of introduction are driven by:

- the rate at which fossil resources are depleted;
- their accessibility for various States and regions;
- limitations on their use imposed by ecological and economic considerations;
- reliability and safety of energy supply;
- principles of sustainable long-term development.

It would be not sufficient to take a simplified approach to resolving energy development problems:

- for a single state or region;
- modelling it as an autonomous system with fixed or predictable (controllable) boundary conditions;
- based on a single scenario, a single plan or a single solution.

Growth in our (human) ability to react properly to continuous changes in the environment will be an essential condition for sustainable development of human society. These changes include:

- natural conditions;
- changes in economic and political conditions;
- dates and time-scales;
- the demands of society, its expectations, anxieties, fears, goals, preferences

Nuclear Power offers opportunity to be a large-scale basis for sustainable development. But several basic **challenges of different types** should be met. This should involve accelerating development in non-technological and technological areas.

- Non-technological areas include economics (short and medium term), public perception of safety and nonproliferation (permanent). These should not just involve technical innovations

and methods for estimating goals and limits, but should also include a “trade-off” mechanism for reaching a social consensus;

- Technological developments include a drastic increase in the scale and rate of fuel mining and enrichment; efficient fuel breeding and a closed fuel cycle for U, Pu, Th, MA; a multi-product and multi-component nuclear energy system; effective separation, transmutation and utilization of radio nuclides; and reliable burning procedures for dangerous radio nuclides.

The IAEA International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) can be considered as the IAEA’s response to the challenges of growing energy demand. In order to make the most of the opportunities and face the challenges of nuclear energy (NE) in the event of its renaissance IAEA Member States need to consider its large-scale development. INPRO proposes a global vision for this development, from which justified guidelines can be derived. The experience gained through INPRO’s assessment studies of Innovative Nuclear Energy Systems (INS) could facilitate the development in non-technological and technological areas to meet challenges of large-scale nuclear energy development.

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