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NUCLEAR ENERGY: LESSONS FROM THE PAST, CURRENT PROBLEMS, AND NEW INITIATIVES

Analysts offer all kinds of scenarios and projections for the future of global energy. But some key points in these projections are immutable: population growth; rising global energy demand; fierce competition for limited and unevenly distributed fossil fuel resources; growing dependence on unstable energy exporting countries; rising environmental concerns; a closing gap in energy consumption between the richest and the poorest countries; a limited and location-specific potential of alternative energy sources; and growing negative consequences of energy shortages brought on by population growth and other factors.

WHAT IS THE FUTURE OF NUCLEAR ENERGY?

In such circumstances, the role of nuclear energy—as the only new industrial-scale energy source capable of answering all these challenges—is undoubtedly set to grow. The volatility of the fossil fuel market (and the oil market, first and foremost), as well as the latest financial crisis, only serves to emphasize the importance of nuclear energy.

For many countries, especially the United States, nuclear technologies are not merely an element of the energy market. Perhaps even more importantly, they are the foundation of our economic, energy, and political security. They are also the basis of our social development in such areas as:

- nuclear medicine (new diagnostic and treatment methods for heart disease, cancer, etc.);
- food production and distribution (including safe new techniques of food storage);
- industrial quality control methods;
- nuclear-physics technologies, instruments and products (such as lasers, accelerators, and isotopes).

For Russia, nuclear technologies are a powerful instrument for building a high-tech economy, and for ending dependence on exports of raw materials by developing high-tech industries, with a key role played by education, the environment, and A safety culture as new engines of social and economic growth. Nuclear technologies are capable of delivering a five-fold increase in the proportion of machine-building and high-tech sectors in the structure of the Russian economy.

Speaking at the UN Millennium Summit in 2000, the Russian president proposed an initiative which highlighted nuclear technologies as the basis of energy security and sustainable development. The initiative was very timely, and it found a lot of support among the international community.

The initiative was also backed by several resolutions of the IAEA General Conference, which issued a recommendation to use it as the core of the INPRO international project involving 30 countries, and made it part of the agency's regular program.[1]

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The UN General Assembly also welcomed the Russian presidential initiative in its resolutions, describing it as an answer to the aspirations of the developing countries and as a way of harmonizing relations between the industrialized and the developing world.[2] But the actual implementation of that initiative (including as part of the INPRO project[3]) and analysis of the possible scenarios for nuclear energy development have demonstrated that nuclear energy and nuclear technologies themselves still require substantial improvement and innovation.

Following the accident at the Fukushima nuclear power plant in Japan the international community has been discussing a broad range of issues, from the future of the nuclear energy renaissance to the need for a new global regime of not only nonproliferation but also nuclear and radiation safety and security. Experts and decision-makers are discussing the need to set up new bodies, develop innovative governance methods, and implement compulsory new international standards.[4]

But these discussions often ignore the fact that the nuclear technologies in use today are 20 to 30 years old; that includes light water reactors, i.e. the VVER, PWR, and BWR reactor designs, as well as fast neutron reactors. More than 80 percent of the world's nuclear power plants rely on water-cooled and water-moderated thermal neutron reactors. That, in fact, is one of the key reasons for the stagnation of the nuclear energy industry in the leading Western countries.

Figure 1 illustrates why the current generation of nuclear technologies cannot underpin future growth. These technologies are completely reliant on U-235. The global reserves of that uranium isotope are actually an order of magnitude smaller than the reserves of oil and gas. How, then, can we expect nuclear energy based on such technologies to have any long-term future, or any stabilizing role?

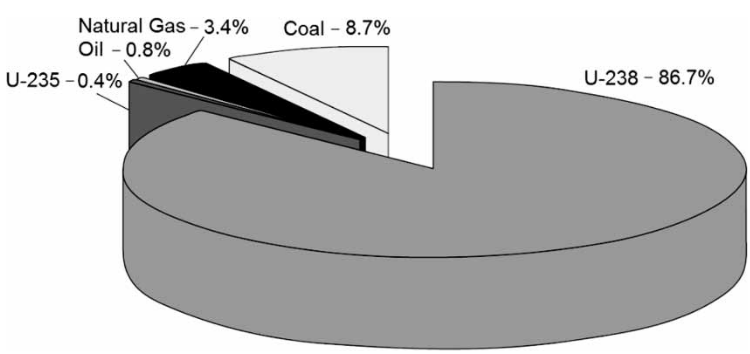
Another major problem is that at this point nuclear energy is used only for industrial-scale electricity generation. But the bulk of the natural energy resources (i.e. fossil fuels) are actually being consumed by such applications as industrial heating, central heating, and transport, where nuclear energy currently plays a marginal role.

More than 60 years since it was developed, high-temperature gas-cooled reactor technology (HTGR) still remains underutilized; only a few research and semi-industrial reactors have ever been built. Such reactors were at one point expected to become the basis of a nuclear-hydrogen energy industry by generating synthetic liquid fuel. That would enable nuclear energy to be used in transport and industrial heating (800°C and above) applications.[5]

Another technology which is not being utilized is nuclear-powered central heating plants. Russia began to build such plants in Nizhniy Novgorod and Voronezh, but then abandoned the projects.

Yet another technology that could be put to a much better use is small energy reactors (with an output of less than 100 MWe), which could be very attractive for the developing countries and as an autonomous power source in off-grid locations. In Russia, for example, only 12 percent of the territory is covered by the electricity grid and suitable for large nuclear power plants (1,000 MWe

Figure 1. **Relative Energy Content of Natural Fuel Sources (Energy), Not Counting Renewables**



Source: *Nuclear Technology Review 2006,* ''Key Issues'' (Vienna: IAEA 2006), pp. 12–20.

and above). Very promising designs have been proposed by foreign and Russian engineers (4S in Japan, PRISM in the United States, SVBR in Russia, etc.)—but none of them has been commercialized. That is especially surprising in the case of the United States and Russia (Soviet Union), which have accumulated vast experience in this area, having built about 1,000 small reactors for nuclear-powered submarines.[6]

The key problem of sustainable development is the problem of utilizing the reserves of natural uranium and thorium for nuclear energy. It is important to stress that solutions here can be found. These solutions require innovative new technologies, and a new technology platform. Let us therefore look at these technologies in greater detail, because the existing technological approaches not only fail to address the problems of future sustainable development of nuclear energy, but can actually pose additional obstacles.

INNOVATIVE TECHNOLOGIES AND PROLIFERATION RISKS

A radical solution, a solution that has already been validated by experiments and semi-industrial scale application, has actually been available for a long time. Back in 1944 Enrico Fermi proved the possibility of utilizing the reserves of natural uranium and thorium (which are almost unlimited) by using fast-neutron reactors in a closed nuclear fuel cycle (NFC).[7] In this day and age it is almost undisputed that full-scale development of nuclear energy as a basis of sustainable growth can be achieved only by using a closed nuclear fuel cycle and fast breeder reactors.[8] That is precisely the global objective now being pursued by leading international projects such as INPRO (launched on Russia's initiative in the IAEA framework) and GIF IV (the fourth-generation reactor project spearheaded by the United States and involving only the leading nuclear countries).

The task has turned out to be much more complex technologically and politically than the nuclear energy pioneers had envisaged. To understand why, let us look at the background of the fast reactor technology.

Research into fast neutron reactors has been under way for more than six decades. In 1944 Fermi proposed the original concept of fast reactors. In 1946 the United States launched the first experimental fast reactor, codenamed Clementine, which worked on plutonium and used mercury as the coolant.[9] In 1951 the EBR-1 experimental breeding reactor in the United States generated the first nuclear electricity.[10]

The EBR-II was the world's first reactor to utilize a closed nuclear fuel cycle; the project was conducted in 1964–1968. The reactor used metallic fuel and liquid metal as coolant. The JFR nuclear fuel cycle involved metallic vapor processing and recycling of actinides (uranium, plutonium, etc.) from spent fuel.[11]

In the Soviet Union research into fast reactor technologies began in 1949; the project was led by Alexander Leypunsky. In 1956 the Soviet Union launched the BR-2 experimental breeder reactor, which was similar to the Clementine. Then in 1959 it was replaced by the BR-5 (built at the FEI institute in Obninsk), which had a thermal power output of 5 MW. The BR-5 was the prototype of the future BN-type reactors (oxide fuel, cooled by liquid sodium). In 1973 the Soviet Union launched the world's first semi-commercial BN-350 reactor in Kazakhstan, and in 1980 the BN-600 reactor at Beloyarskaya NPP. The BN-600 is currently the world's only operational fast-neutron energy reactor. Nevertheless, Russia has never been able to implement a closed uranium–plutonium nuclear fuel cycle. The BN-type reactors (BN-350 and BN-600) have always worked in an operational mode which consumes uranium (enriched to more than 20 percent) rather than breeder mode.

Development of a new type of reactor with liquid-metal coolant had taken a lot of research and efforts by three or four generations of scientists. But even in those countries which have developed such technology (such as the United States) the fast reactor and closed NFC know-how and expertise have largely been lost. It has now become obvious that this was a policy mistake by the United States, which shut down almost all of its fast reactors and closed NFC programs in the 1970s.[12]

That loss of know-how and expertise was not merely an economic loss, and a waste of tens of billions of dollars. It was in fact a real science and technology catastrophe; an entire branch of research was allowed to fall apart, and leadership in the area of important nuclear energy technologies was lost. The losses include:

- ❑ professional and highly trained specialists;
- ❑ a system of higher education in the relevant area, including professors and researchers;
- ❑ experimental facilities and laboratories;
- ❑ new generations of young scientists.

Rebuilding the things which have been allowed to crumble will take decades of energetic efforts, and may in fact prove impossible.

The main obstacle on the way to rebuilding these branches of research and developing an innovative technology platform for nuclear energy development is the need to train a new generation of specialists. Such training programs should always be several steps ahead of the actual research programs and projects to build nuclear energy facilities. Launching new nuclear power plants (NPPs) and other nuclear facilities is simply dangerous unless there is an adequate personnel training policy in place.[13]

GLOBAL NATURE OF NUCLEAR TECHNOLOGIES AND NATIONAL SOVEREIGNTY

The international community—including the IAEA, other international nuclear organizations, and national nuclear laboratories—has learned important lessons about radiation and nuclear safety and security, environmental problems, and other aspects of nuclear energy development. That experience has been reviewed and analyzed once again following the accident at the Fukushima NPP. There are good reasons to believe that the bulk of these problems can be resolved by new technologies and engineering solutions.

The only major problem which cannot be resolved through technology alone, and which requires political solutions, is the problem of nuclear nonproliferation. There is a serious conflict between the global nature of nuclear technologies (a nuclear accident always has global repercussions) and the national nature of responsibility and control; in other words, national sovereignty often gets in the way of resolving global problems. In some sense, the proliferation problem is only going to get even worse as innovative technologies continue to make progress. New fast breeder reactors, reprocessing and recycling of fissile materials, transmutation, large numbers of small NPPs, increasing numbers of nuclear specialists, a growing need for transportation of nuclear materials, and other factors (see Tables 1 and 2) will increase the risk of proliferation of sensitive nuclear expertise, materials, and equipment.

SCIENCE, TECHNICAL AND POLITICAL COOPERATION

When nuclear energy and nuclear weapons research was still in the early stages, luminaries such as Fermi, Szilard, and Einstein were already warning about the global consequences of that

Table 1. **Proliferation Risk Factors**

Growth of the nuclear energy industry	
1	Growing numbers of nuclear power plants, including small regional NPPs
2	Growing numbers of nuclear fuel cycle facilities
3	Growing need for transportation of nuclear materials
4	More nuclear waste
Structural changes in the nuclear energy industry	
1	Nuclear fuel breeding, use of fast breeder reactors
2	Spent nuclear fuel reprocessing and recycling, closed nuclear fuel cycle
Growth of the nuclear energy industry in newcomer countries which do not have the necessary expertise to ensure proper nuclear security, safety, and nonproliferation standards	

Source: *Nuclear Technology Review 2006* ''Key Issues'' (Vienna: IAEA, 2006), pp. 12–20.

Table 2. **Ways to Boost the Resilience of the Nonproliferation Regime**

Changes in the nuclear industry can lead to greater availability and accessibility of nuclear materials and technologies, thereby increasing proliferation risks	
New approaches and measures are required to keep those risks from getting worse, at the very least	
Measures that are necessary in all areas which underpin the regime	Political Institutional Technical
Systemic analysis and quantitative assessment of the proliferation risks are required to address these problems	

Source: *Nuclear Technology Review 2006*, ''Key Issues'' (Vienna: IAEA, 2006), pp. 12–20.

research. They predicted that nuclear energy would play a key role in the future—but they also warned of the need for a reliable international system of nuclear safety and security. What they had in mind was not merely technologies enabling safe use of nuclear energy, but also a security regime to prevent a runaway proliferation of nuclear technologies and to place them under international controls.[14]

One of the key initiatives in this area was the Atoms for Peace program initiated at the United Nations by U.S. President Dwight Eisenhower in 1953. The initiative quickly garnered broad international support, and in 1954 the UN General Assembly adopted a resolution which backed the program. One of its key elements was the decision to establish the International Atomic Energy Agency (IAEA).

The IAEA Statute was approved in 1956, and the organization itself was set up the following year. In 1955 Geneva hosted the first international conference on the peaceful use of nuclear energy. Similar events attended by renowned nuclear scientists were held in 1958, 1964, and 1971. These events launched practical international cooperation on the peaceful use of nuclear energy.

A key factor in further development of peaceful use was the entry into force in 1970 of the Nuclear Non-Proliferation Treaty. At about the same time several regional organizations were set up to consolidate national efforts and to provide additional guarantees of peaceful and effective development of nuclear science and technology. These organizations include the Nuclear Energy Agency and the International Energy Agency in the OECD countries, Euratom in the European Union, etc.

The global nature of the development of nuclear technologies was also reflected in the creation of several specialized international organizations, including the World Association of Nuclear Operators (WANO); the World Nuclear Association (WNA), which brings together nuclear industry companies and organizations; the World Nuclear University (WNU); and several others. Another element of the same trend is the Kyoto Protocol, which also reflects the global nature of the world's energy problems.

INTERNATIONALIZATION OF THE DEVELOPMENT OF NUCLEAR TECHNOLOGIES

The establishment and development of global (multinational) nuclear energy organizations was happening in parallel with the realization of the key role of nuclear fuel cycle technologies in resolving the nonproliferation problem. In the 1970s–1980s the world began to discuss various ideas, concepts, and proposals on international integration of the nuclear fuel cycle (one notable event was a workshop in Salzburg in 1977[15]). The ideas included:

- ❑ creating regional NFC centers;
- ❑ establishing international centers for handling spent nuclear fuel and plutonium.

An important stage in the discussion of various NFC concepts was the international nuclear fuel cycle assessment conducted in 1978–1980 with active participation of experts from 18 leading countries. But for various political and economic reasons—including the great political and economic importance of nuclear technologies for the economies of many countries—until the end of the twentieth century those discussions and proposals remained on paper.[16]

INTERNATIONAL NFC CONCEPT: THE CURRENT STATE

Several very important initiatives were put forward at the turn of the twenty-first century to bolster international cooperation in the area of nuclear technologies, which are seen as the basis of sustainable energy development. These include the initiative proposed by Russian President Vladimir Putin at the UN Millennium Summit in 2000; and the U.S. initiative which has resulted in the establishment of the GIF IV International Forum. The latter aims to develop innovative fourth-generation reactor technology and a nuclear fuel cycle. These initiatives came as a harbinger of a more mature approach to nuclear energy development, which takes into account the mistakes and lessons learnt in the previous years—including the lessons of Three Miles Island, Chernobyl, etc. That has required meticulous analysis of all the positive and, most importantly, negative experiences.

The following things have become absolutely clear to experts and specialists:

- ❑ Future sustainable economic growth and energy security on a global scale, taking into account the needs of the developing countries (especially China, India, Brazil, Argentina, etc.) are impossible without nuclear energy. In addition to power generation, nuclear energy has other important applications in healthcare, food and water supply, science, technology, and industry, etc.

- ❑ There are technological solutions available for such key nuclear energy problems as safety and security of nuclear power plants and nuclear fuel cycle facilities—including the problem of spent nuclear fuel management and nuclear waste disposal. The important thing is to secure sufficient financial, material, and human (intellectual) resources.

Further nuclear energy development is facing only one major challenge for which no obvious solutions have been proposed: the problem of nuclear nonproliferation. This is a complex technological and political problem consisting of three individual components, each requiring its own solution:

- ❑ accounting of fissile materials (part of the IAEA remit);

- ❑ technological and design barriers to proliferation;

- ❑ measures such as international agreements, conventions, and other solutions.

The world has also come to the realization that almost every step in the development of NFC technologies can also be viewed as a potential step towards military use of nuclear technologies. The focus has therefore shifted to the question of how to make use of the benefits of nuclear energy without the risk of proliferation of NFC technologies (especially enrichment, production of highly enriched uranium, spent fuel reprocessing, and the use of plutonium fuel). In 2003 a group of experts from leading nuclear countries published an IAEA-commissioned report ''Multilateral Approaches to the Nuclear Fuel Cycle'' (INFCIRC/640). In 2004 the World Nuclear Association published another report, headlined ''Ensuring Security of Supply in the International Nuclear Fuel Cycle.'' Several individual countries (the United States, Russia, Japan, Germany, and others) have also proposed various national initiatives in this area. The following three initiatives are probably the most comprehensive:

- ❑ international NFC centers for nuclear fuel enrichment and spent nuclear fuel processing (Russia);

- ❑ international nuclear fuel banks for assured access to NFC products and services (Russia, Germany, the WNA, and others);

- ❑ the Global Nuclear Energy Partnership (GNEP), proposed by the United States and supported by more than 20 countries.

The obvious question is, how can we make sure that these latest initiatives do not remain on paper—which is exactly what has happened to all the earlier initiatives? How can we overcome the passive or even hostile attitude to these initiatives by several countries which see them as discriminatory—even though their proponents say the objective is to help the developing nations in peaceful use of nuclear energy?

EFFECTIVE DEVELOPMENT OF NUCLEAR ENERGY

Let us briefly summarize the problems facing nuclear energy technologies as a solution to the world's energy problems. It has now become obvious that the task of developing nuclear weapons has proved easier to accomplish than the task of developing modern nuclear energy reactors and nuclear fuel cycles. It will be impossible to make the best possible use of nuclear energy without commercializing the breeder reactor technology with a closed NFC.

Of the six types of future nuclear reactors selected for the GIF IV international project, four are fast-neutron reactors. Three of them use liquid metal (sodium, lead, or lead–bismuth alloy) and one uses gas (helium) as the core coolant.

Development of the breeder reactor technology (including fast reactors using the uranium–plutonium NFC and slow neutron reactors using the thorium NFC) has been ongoing for over 60 years. In 1968 the United States launched the MSBR thorium-cycle molten-salt breeder reactor at the Oak Ridge National Laboratory. The reactor, which had a breeding ratio of more than one (1.06),[17] remained in operation for seven years.

For more analytics on international nuclear energy cooperation, please, visit the ''Development of Russia's Nuclear Exports'' project section of the PIR Center website at: atom.eng.pircenter.org

Experiments conducted using the world's first semi-commercial fast-neutron reactor, the BN-350 (Kazakhstan, Soviet Union) achieved a breeding ratio of 1.3 for the plutonium fuel cycle. A French fast-neutron reactor has achieved an industrial-scale closed NFC with repeated fuel recycling and a breeding ratio of 1.2–1.3.[18] The Beloyarskaya NPP in Russia, which operates the BN-600 fast-neutron reactor, has been working reliably since 1980; an upgraded BN-800 version of the reactor is now under construction. None of the BN-type reactors, however, is currently being operated in the fuel breeder mode.

There is still no single concept (or demonstration) of a commercial fast energy reactor with a closed NFC. Development of innovative new NPPs (fast reactors, as well as high-temperature gas-graphite reactors for nuclear-hydrogen applications, or supercritical PWR reactors), which is one of the objectives of the INPRO and GIF VI international projects, has turned out to be too complex and expensive for any single country (even such leaders as the United States, the former Soviet Union, France, Japan, etc.). In actual fact, financing is not the biggest problem. Serious nuclear accidents, including the recent accident at the Fukushima NPP in Japan, have demonstrated that there is no more room for mistakes. Specialists agree that another serious nuclear accident would spell the end of nuclear energy.

Development and implementation of fast reactor projects with a closed NFC has proved too great a task for a single generation of researchers and engineers. It has also become clear that this task requires the kind of technological expertise which only a very limited number of countries possess (including France, Russia, Japan, and India). Re-building lost expertise in this area is one of the main objectives of the U.S.-sponsored GIF initiative, which aims to develop fast reactors with a closed NFC.

Developing a commercially viable fast reactor with a closed NFC is not, however, the only task that must be accomplished to facilitate the development of nuclear energy. There is also the problem of dealing with highly radioactive waste, which must be addressed at the regional level at the very least because it is so complex, expensive, and dependent on specific conditions in some countries (such as the densely populated Western European or Southeast Asian nations).

Another related problem is the need to develop and commercialize the technology for transmutation of long-lived fission products and disposal of actinides generated by fast reactors. A similar solution is also required for the thorium fuel cycle.

Effective solutions to these global problems are impossible without international cooperation. They require the pooling of financial, material, and, most importantly, intellectual resources of the countries which have the necessary expertise, technological capability, and industrial infrastructure.

In order to achieve a consensus in addressing the problem of nonproliferation, as well as NFC security and safety, proponents of multilateral nuclear energy initiatives must demonstrate how the developing and small countries (such as the Eastern and Central European nations) can benefit from these initiatives in the long term, and not just in the immediate future. We must not delay studying, discussing, and demonstrating the need for cooperative solutions to nuclear energy problems based on such initiatives as the International NFC Centers and the Global Nuclear Energy Partnership. This includes the need to establish and develop:

- NFC enrichment centers (which is something Russia has already proposed) to provide the developing and small countries with low-enriched uranium fuel;
- NFC spent nuclear fuel removal centers (the proposal is currently being discussed);
- NFC centers specializing in processing spent nuclear fuel and extracting plutonium from it;
- NFC centers specializing in producing plutonium fuel for fast reactors and in utilizing that fuel in fast-neutron reactors;
- NFC centers specializing in the production of U-233 in fast reactors (with thorium screens) and using that uranium to make low-enriched (synthetic) fuel for thermal reactors: U-233 + U-238 (for long-term provision of fuel to developing and small countries);
- NFC centers specializing in nuclear waste disposal.

Obviously, some NFC centers can specialize in more than one of these six areas; for example, removal of spent nuclear fuel can be combined with spent fuel processing and extraction of plutonium. A comprehensive solution to all these problems can only be found through international cooperation because it requires enormous financial, material, and human resources. No country can do it on its own.

The goals and objectives outlined in this paper are truly a global goal of the century. Unless these goals are achieved, we may see the spread of sensitive nuclear technologies, including enrichment and spent fuel reprocessing, with potentially a dozen new countries acquiring nuclear weapons by the middle of this century. The small and developing countries must see the need for and the benefits of the multilateral nuclear initiatives; they must understand what changes they must make in their national programs, and clearly see all the upsides and downsides of participation.

Such an approach will also require research and analysis in the following areas:

- analysis of the requirements for the infrastructure of the states taking part in multilateral initiatives (in areas such as education, controls in the knowledge transfer system, regulating bodies, engineering and technological infrastructure, etc.);
- analysis of the program for managing and preserving nuclear know-how under the IAEA's auspices to ensure that knowledge and experience are passed on to the next generations of specialists (this is a separate problem in which the IAEA must play a leading role) and to new developing countries.

Successful implementation of these initiatives will be instrumental for ushering in a new era of nuclear energy development, sometimes described as a nuclear renaissance.

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