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Research Article

Critical notes: history, state, problems and prospects of nuclear science and technology*

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Abstract

This paper does not contain new computational and experimental scientific results. It attempts to analyze, based on a simplified phenomenological approach, the methodology of the evolution histories of nuclear science and technology, as well as the contradictions and issues which, if not resolved, make senseless any discussions of scenarios for the full-scale evolution of nuclear power.

The paper analyzes in brief the evolution history of nuclear technologies in the USA and in the USSR. It also considers the present-day state of nuclear power. Two international projects, INPRO and GIF IV, were initiated in 2000. The INPRO objective is to define the evolution strategy for and the requirements to the nuclear power of tomorrow. The GIF IV project aiming to develop Generation IV reactors for future NPPs focuses on building innovative reactors capable to cope with the challenges involved in further evolution of nuclear power.

The following issues were considered as the result of the system analysis

- further evolution of nuclear power worldwide;
- nuclear non-proliferation;
- NPP safety;
- nuclear waste;
- climate and oxygen burning in the NPP operation;
- education and training of younger generations of nuclear workers.

A critical analysis into the history, status and future evolution of nuclear technologies at the present-day stage shows that the nuclear energy market has monopolized the design, development and construction of practically only one type of nuclear reactors for NPPs (95% of the NPPs under construction have water-cooled water-moderated reactors) which explains the fact that single-skilled personnel are largely trained for the construction and operation of this plant type.

Achieving the full-scale evolution level of nuclear power capable to cope with the socio-economic and ecological issues faced by humankind requires a basically new evolution concept for all fields of nuclear industry.

Keywords

Nuclear power, nuclear technologies, system analysis of nuclear power

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1. Introduction

To analyze the evolution stages of nuclear science and technology that determined the creation and development of nuclear weapons and, later, nuclear power, one needs to go back to the early 20th century, that is, to more than 100 years ago. Neutrons had not yet been discovered then and no acceptable theory of nuclear structure existed while the possibility of a nuclear fission chain reaction was not even an issue of discussion, but it was as soon as in 1910 that Vladimir Ivanovich Vernadsky, a prominent Russian scientist, made a report on new nuclear forces, based on radium radioactivity investigation results, to the Russian Academy of Sciences. At the time, there were experiments known conducted by the Nobel Prize winners, Marie Skłodowska Curie and Pierre Curie. Vernadsky realized that the discovered nuclear forces were million times as efficient as the known chemical forces. So, accordingly, he suggested that humankind was entering a new era when there would be no limits on access to energy and all of the nourishment, health, and industrial and social development problems would be resolved (Vernadsky 2013).

This was one of the first predictions about the coming Golden Age of humankind based on a scientific and technological revolution. Later, however, when the Radium Institute was opened in 1922, he was first to understand the full extent of the tragic drama brought about by this opening of the 'door' not only to a brighter future but also to the potential self-destruction of humankind as the whole. When addressing an audience of scientists and public figures (Vernadsky 1922), he said:

"We are approaching a great change in the life of humankind, the one incomparable with all those experienced by it before. The time is near when man will acquire atomic energy, the source of such a force that will make it possible for him to build his life as he desires. This may occur in several years to come or in a century. But it is clear that it is bound to happen.

Will man be able to take advantage of this force and to use it for benefit and not for self-destruction?

Is he mature enough to use the force that science is inevitably bound to give him?

Scientists shall not turn a blind eye to the potential consequences of their scientific work and the scientific progress. They must feel responsible for all of the consequences their discoveries bring. They must connect their work to the best organization of the entire mankind".

2. History of nuclear power evolution. A brief review

In December 1942, a team led by Enrico Fermi, an Italian scientist and Nobel Prize winner, started the world's first uranium-graphite nuclear reactor based on natural uranium (CP-1, Chicago Pile 1). Later, the reactor was dismantled and moved, under the name of CP-2, to the Argonne National Laboratory (ANL) established in the USA. It was two years later, in 1944, that the world's first heavy-water natural-uranium reactor (CP-3) was started at the ANL. These two types of natural-uranium reactors formed the basis for the evolution of plutonium production industry. In parallel, the uranium enrichment technology was evolving successfully. These two technologies made it possible to begin to build nuclear weapons (Andrianov et al. 2012).

The first, plutonium, nuclear bomb was detonated by the USA in July 1945. This Trinity explosion is considered the beginning of the nuclear era. The two next (uranium and plutonium) nuclear bombs were detonated over Japan.

The successful nuclear weapon testing focused the efforts of scientists, engineers and technologists from the allied countries on the creation of nuclear weapon arsenals and delivery vehicles, the key priority national task of their survival.

This moved the evolution of nuclear power and the advent of the Golden Age of energy prosperity to the sidelines of national scientific and technical progress for a decade.

At 7.00 AM local time on 29 August 1949, the Soviet Union's first nuclear charge, RDS-1, was detonated at the Semipalatinsk test range.

Nuclear problem required the involvement of experts in a great variety of fields of science and technology, including metallurgists, mechanics, chemists, biologists, textile technologists, and glass experts. This was a systemic problem and it could be resolved only through the joint work of as many persons with the greatest scientific and technological expertise as possible. The USSR hurled all of the country's efforts into resolving this complicated and important problem and the required basis was fully formed. The nuclear industry infrastructure was simultaneously established as the groundwork for the further nuclear evolution of the nation.

This solved conceptually the problem of nuclear weapon building in the USSR and eliminated the US nuclear monopoly. Further, as the result of the nuclear arms race, over 1550 nuclear tests were conducted and more than 8500 nuclear charges were built in total in the USA and in the USSR during the cold war period.

Simultaneously, the problem of nuclear weapon delivery was being resolved in the USA and in the USSR. Enormous resources (material, technical and financial) were spent to build over 500 nuclear submarines equipped with about 1000 nuclear reactors and missiles carrying nuclear warheads. The number of states possessing nuclear weapons (nuclear powers) started to grow as Great Britain, France, and China joined the USA and the USSR. The threat of nuclear weapon proliferation emerged.

In 1954, following a prolonged debate, the UN General Assembly passed a resolution on establishing international control of the development and use of nuclear technologies and setting up the International Atomic Energy Agency (IAEA) to supervise its enforcement.

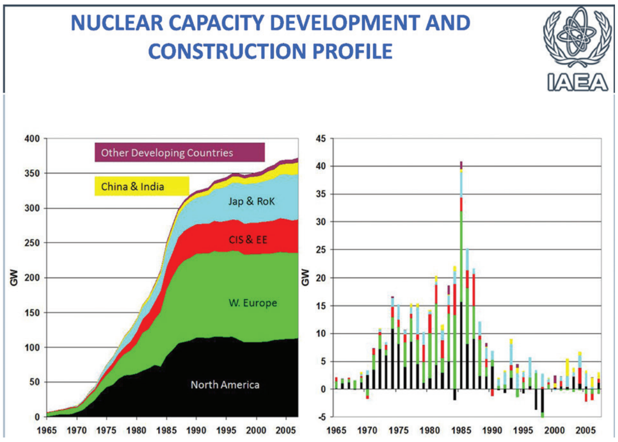

Figure 1. Growth of NPP capacity in the world (by regions), and the number of new NPPs constructed annually (Andrianov et al. 2012).

As the initial practical step, it was decided to hold the First Geneva Conference on Peaceful Uses of Atomic Energy under the UN auspices, where ways for peaceful uses of atomic energy could be discussed. Quite a sensation was created at the conference by a report on the world's first nuclear power plant started in 1954 in the city of Obninsk in the USSR (5 MWel) with a water-cooled uranium-graphite reactor based on enriched uranium (AM-1).

Later, in 1956, the world's first commercial NPP, Calder Hill, (50 MWel) with a carbon dioxide cooled uranium-graphite reactor based on natural uranium was started in England. It had a MAGNOX-type nuclear reactor developed for weapon-grade plutonium production.

In 1957, the world's first NPP (Sheppingport of 70 MWel) was started with a water-cooled water-moderated reactor of the PWR type (the VVER type in Russia). This reactor type was developed for the nuclear submarine nuclear propulsion system and forms currently the basis of present-day nuclear power.

A conceptually important step was the startup by E. Fermi's successors in 1946 in the USA of the world's first fast-neutron reactor (without moderator), Clementine (CP-4), in which plutonium was used as fuel. This was the first time that liquid metal (mercury) was used as coolant (Andrianov et al. 2012).

This caused a rapid growth in the number of NPPs worldwide (see Fig. 1) based on the platform formed by nuclear weapon projects, including the fuel base and the whole of the industry infrastructure in a range from uranium mining to fabrication and in-pile use of nuclear fuel, personnel training, and expertise.

More than that, the world's first launched NPPs of different types were actually the result of the conversion to the development of designs for military applications (Andrianov et al. 2012).

3. Current state of nuclear power

By the mid-1980s, there were not less than 40 nuclear units under construction worldwide, and the total power of nuclear facilities reached more than 350 GWel. Everything was going perfectly well until 1979 when an accident, the largest one in the history of commercial nuclear power in the USA, occurred at Three Mile Island, a nuclear generating station, leading to substantial economic losses (over 200 orders for the construction of new NPPs with the most widespread reactor type, PWR, were cancelled). This was followed by the 1986 accident at the Chernobyl NPP which grew into a nuclear disaster with both economic and global socio-political consequences. It was the Soviet Union that was largely affected as the world's only maker of this reactor type. However, there was a sharp rise in negative public attitudes towards nuclear across Europe. Seven small countries decided to ban nuclear development.

The evolution of nuclear power started to decay by the end of the 20th century. The concept of NPP safety and further development of "nuclear safety culture" as one of the bases for nuclear power began to be revised. The aphorism by H. Blix, the IAEA Director General, that "a nuclear accident anywhere is an accident everywhere", became a manifest truth (Andrianov et al. 2012).

Two international projects (Fig. 2) were organized in 2000 to find the way out of the crisis in the development of nuclear power. The Russian-initiated INPRO innovative nuclear power project has been evolving under the IAEA auspices and unites the efforts of experts from nuclear developed and developing countries (over 40 countries).

The INPRO objective is to define the evolution strategy for and requirements to future nuclear power.

The project to develop generation IV reactors for future NPPs (GIF IV) aims to build innovative reactors (Fig. 3) expected to resolve (after 2030) the problems of further nuclear power evolution, including in terms of safety, economic efficiency, unlimited development resources, waste handling and spent fuel non-proliferation (Fig. 4). The stakeholders in the US-initiated project are only 11 most nuclear developed countries (Russia and China joined GIF IV in 2006).

Unfortunately, the situation worsened sharply as the result of the 21st century's gravest nuclear accident. It occurred in

Figure 2. Base documents of INPRO and GIF IV, two key international projects (Andrianov et al. 2012).

Generation IV nuclear energy technologies

System	Neutron Spectrum	Fuel Cycle	Size (MWe)	Applications	R&D needed
Very High Temperature Reactor (VHTR)	Thermal	Open	250	Electricity, hydrogen, process heat	Fuels, materials, H2 production
Supercritical-Water Reactor (SCWR)	Thermal, Fast	Open, Closed	1,500	Electricity	Materials, safety
Gas Cooled Fast Reactor (GFR)	Fast	Closed	200-1,200	Electricity, hydrogen, actinide management	Fuels, materials, safety
Lead Cooled Fast Reactor (LFR)	Fast	Closed	50-150, 300-600, 1,200	Electricity, hydrogen, production	Fuels, materials,
Sodium Cooled Fast Reactor (SFR)	Fast	Closed	300-1,500	Electricity, actinide management	Advanced recycle options, fuels
Molten Salt Reactor (MSR)	Fast	Closed	1,000	Electricity, hydrogen production, actinide management	Fuel treatment, materials, safety, reliability

Source: Idaho National Laboratory

Figure 3. The list of fourth-generation reactors in accordance with GIF-4 (Andrianov et al. 2012).

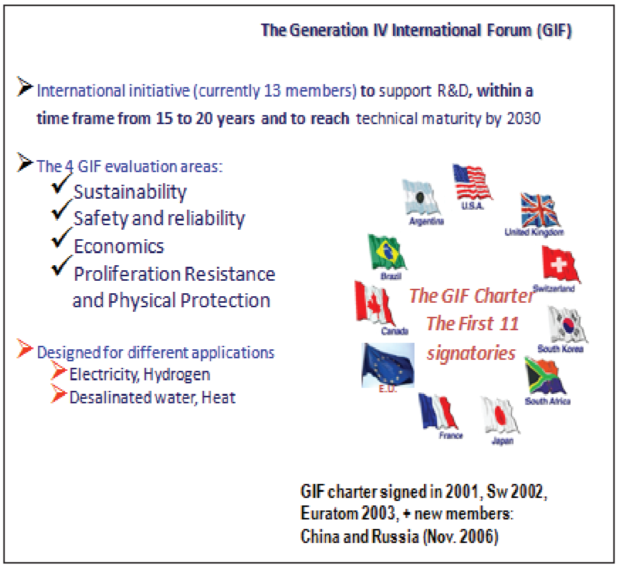

Figure 4. Requirements and objectives of the 4th generation NPP (Andrianov et al. 2012).

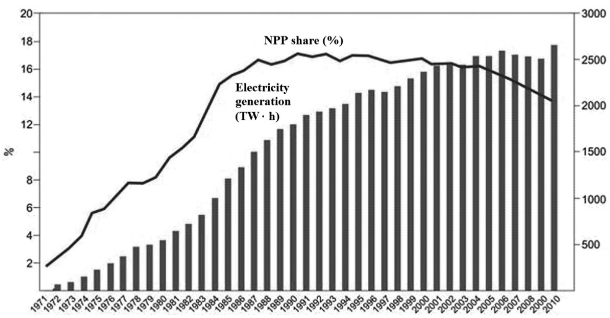

Figure 5. Scale of and reduction in the share of nuclear electricity generation worldwide (Murogov 2019).

2011 at the Fukushima Daiichi NPP in Japan, one of the most industrially and nuclear developed countries in the world.

Nuclear community must find the way out of the existing contradiction: nuclear technology has not yet led humankind into the golden age with energy problems resolved but has made it possible to build a nuclear weapon potential capable to destroy humankind.

In recent years, despite the construction of 54 new units in the world with 5 to 10 NPP units started up annually, the contribution of nuclear power to electricity generation (currently 11%) and to the total energy balance (currently 5%) is decreasing. The reason is not so the decommissioning of outage nuclear units as the rapid growth in the number of conventional and alternative energy sources (Fig. 5).

4. System analysis result

4.1 Problems of further nuclear power evolution worldwide

Let us summarize this brief, shallow analysis of the history of the nuclear science and technology, and on the other hand, the analysis of the current state of nuclear energy, and the problems that complicate its further full-scale development. In this connection, we face a paradoxical situation: what Pioneer Founders thought it unquestionable advantages of nuclear power, turned into its unresolved problems.

Unlimited fuel resources for nuclear power (declared by the industry pioneers) have turned into one of the principal arguments that do not make it possible to call present-day nuclear power a stable energy source. The thing is that the current nuclear power is based on NPPs with water-cooled water-moderated reactors (88.5%) of the VVER – PWR – BWR types using less than 0.5% of the uranium energy potential which, in terms of resources, is 2 to 3 times as small as the available oil reserves (Fig. 6).

There is a well-known conceptual solution to the problem in question. (Practically) unlimited uranium resources become available as nuclear power is evolving based on breeder reactors, such as BN-type fast-neutron reactors. The first liquid-metal-cooled fast-neutron reactor is known to have been started as long ago as in the early days of nuclear power: in 1946 (in the USA, ANL) and in 1956 (in the USSR, the IPPE's BR-2).

After 70 years of development and research, there are only two fast-neutron reactors operating in the world (BN-600 and BN-800 in Russia) out of the total number of about 450 NPP units.

They operate predominantly on uranium-235 (like VVERs) and are not breeders as their nuclear fuel cycle (NFC) is not closed (they do not use on a commercial scale the plutonium separated in the SNF reprocessing).

The idea of breeding based on a fast-neutron reactor and a closed NFC put forward by E. Fermi and given an enthusiastic welcome from his colleagues in 1944 was implemented in the early years of the nuclear era for the increased production of weapon-grade plutonium by reprocessing of SNF from uranium-graphite and heavy-water reactors. As the result, the subsequent development of the CNFC technology in nuclear power for peaceful purposes was, as in the case of the NPP development, the conver-

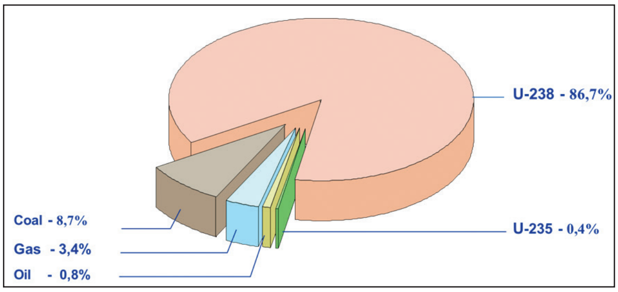

Figure 6. Relative energy content of natural fuel resources. Potential of conventional energy sources and uranium-based nuclear power (Andrianov et al. 2012).

sion of the weapons technology created for production of isotope-pure weapon-grade plutonium. This unqualified transfer of military concepts into peaceful energy technologies laid the basis for the nuclear proliferation risk.

4.2 Problems of further nuclear power evolution worldwide

The establishment of a closed NFC in present-day nuclear power is not simply an expensive and complicated scientific and technical problem. If implemented at the current stage, it may lead to a worsened problem with the proliferation of nuclear-hazardous materials and technologies (Fig. 7).

The thing is that, in the framework of the currently considered two-component evolution model of nuclear power, the SNF processing in a closed NFC will lead, in addition to the existing "sensitive" technology, to one more "sensitive" technology: radiochemical processing or separation, in an explicit form, from a "heap" of irradiated fuel of two potentially hazardous materials (violating the non-proliferation regime): plutonium and high-level radioactive materials (fission products, actinides, etc.). These are products potentially fit for making mass destruction weapons or "dirty" bombs (Fig. 8) (Murogov 2019).

4.3 Safety of NPPs

Full-scale development of nuclear power based on resolving the above three problems (stability – practically unlimited resources, breeders in a closed NFC, non-proliferation of "sensitive" materials, technologies and expertise) is possible only with nuclear and radiation safety of NPPs and the NFC facilities reliably ensured.

An analysis of the nuclear power development has shown a clear dependence of the nuclear power competitiveness on the implementation of the factors listed above. As is known, the cost of a kW of the installed capacity for NPPs with water-cooled water-moderated reactors at the initial stage of the nuclear power development based on the established "nuclear" defense platform (the fuel and industrial infrastructure, education and training of personnel) was about \$200 per kW. The current value is up to \$4000 per kW. What is the major reason for such a sizeable (twentyfold) growth, less inflation?

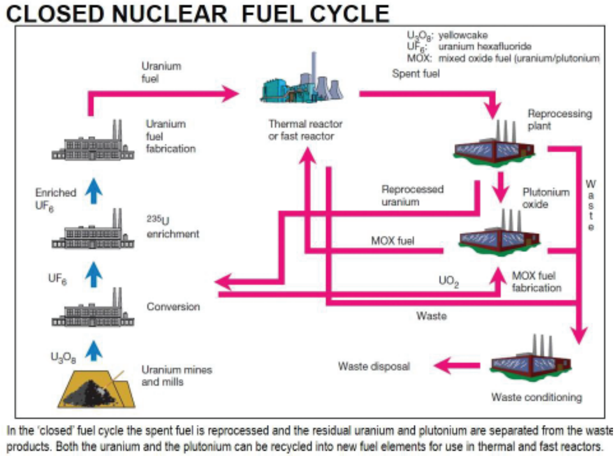

Figure 7. Diagram of a closed nuclear fuel cycle in nuclear power of the 21st century.

Factors influencing proliferation risks

- Increased scales of nuclear power
  - ➤ Growing number of nuclear power plants, including regional small-sized reactors,
  - ➤ Growing number and range of nuclear fuel cycle facilities,
  - ➤ Increased number of nuclear material shipments,
  - ➤ Increased quantity of radioactive waste
- Structural changes in nuclear power production
  - ➤ **Nuclear fuel breeding, use of fast-neutron reactors**
  - ➤ **SNF processing, nuclear fuel cycle, closed nuclear fuel cycle**
- Nuclear power development in nonnuclear countries which are not ready historically to use nuclear technologies (safety and non-proliferation safeguards)

Figure 8. Factors influencing proliferation risks (Andrianov et al. 2012).

As estimated by the NRC (the USA), meeting the growing "engineering" safety requirements alone has led to an annual 10 to 12 % growth in the cost of electricity generation. With regard for additional "penalties" on nuclear power, which do not exist for conventional power, the "market" (market economy) starts to get rid of this uncompetitive technology. This is reasonable from the market point of view. Actually, however, practical use of atomic energy began as a vital national task. And it is exactly the way it is going on in the field of nuclear weapons while nuclear power has been left completely at the mercy of the market (Murogov 2019).

4.4 Nuclear waste problem

In the early evolution stages of the peaceful uses of nuclear power, due to its high concentration, unlimited quantities (with a possibility of close supervision, accounting and isolation) and gradual radioactive decay, nuclear waste was believed to provide nuclear power a competitive edge.

However, the presence of long-lived high-level waste and actinides (primarily plutonium) requires long-term supervised disposal of radioactive waste (for hundreds of thousands and millions of years) which is unique in human history. It is no coincidence that a priority program has been established and is evolving within the IAEA for preserving nuclear knowledge for future generations, including for unique long-term preservation of the waste disposal knowledge.

As far as the long-lived high-level isotope transmutation technology is concerned, this process requires special-purpose fast-neutron reactors with highly excessive quantities of isotopes (the so-called burner reactors), which exist at the present time only at a conceptual level (Murogov 2019).

An analysis of the nuclear science and technology development history makes us give thought to about a hundred year old prediction by Vladimir Ivanovich Vernadsky on the global consequences of the nuclear technology evolution and implementation.

4.5 Climate and oxygen burning – role of nuclear power

Therefore, on the one hand, the analysis shows that we have a global effect in the form of the established modern nuclear weapon system, and, on the other hand, the development of the current-level nuclear power has encountered a number of problems that hinder its full-scale evolution to the level defining the global evolution of power.

Meanwhile, the challenges faced by mankind and caused by the industry-related human activities require exactly global changes that are beyond the scope of market relations. That is, the question is about the need for introducing public regulation in economic activities (including, industry, transport, and agriculture).

Actually the first such step was the establishment of the international nuclear regime under the UN auspices (the formation of the IAEA, NPT, etc.). This was followed by the Kyoto Protocol and the Paris Agreement that impose certain restrictions on industrial activities of the signatory states.

“Thousands of cubic meters of hydrogen, methane and other gases, including carbon dioxide and water vapor both from volcanic activity and catastrophic fires, and from industrial activities leading to the greenhouse effect on the planet Earth, are released periodically into the atmosphere. Water vapor is “sequestrated” in the atmosphere by its gradual condensation, and carbon dioxide is “sequestrated” in the course of many and many thousands of years in the biomass of the planet’s plant life as the result of a photosynthesis reaction with formation of molecular atmospheric oxygen, the energy basis of our present-day civilization” (Fig. 9) (Boldyrev 2016).

From the energy point of view, photosynthesis is the process of photo energy accumulation into potential chemical energy of the interaction among photosynthesis products (atmospheric carbons and oxygen).

$$6CO_2 + 6H_2O + \text{SOLAR ENERGY} = C_6H_{12}O_6 + 6O_2. \quad (1)$$

Along with the broadly discussed “greenhouse” aspect of the accumulation of carbon dioxide, water vapor, methane and other gases in the atmosphere, protection of atmospheric oxygen against its industrial consumption is a top-priority goal in regulation of relations between man and nature!

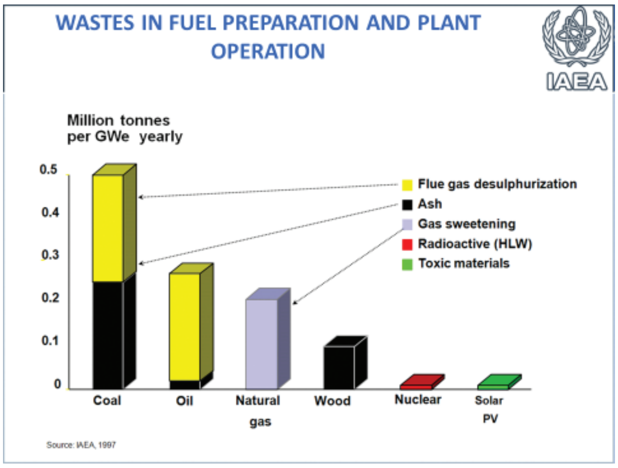

Figure 9. Comparative analysis of various energy sources (red – with regard for activities in their fuel cycle) in terms of greenhouse gas generation (Andrianov et al. 2012).

Most industrially developed countries have long become parasitic countries in the territories of which the industrial consumption of atmospheric oxygen exceeds many-fold its reproduction (pure primary product) by the plant life. Russia, Canada, the Scandinavian countries, Australia, Indonesia, and other countries are donors which provide parasitic countries with their oxidant (atmospheric oxygen). The industrial use of oxygen in West European countries exceeds five- to six-fold its “vital” consumption for human breathing (Boldyrev 2016).

Atmospheric oxygen needs to be permanently and continuously recovered by the planet’s plant life as the result of photosynthesis in the amount that takes into account its anthropogenic consumption as well.

At the present time, however, commercial consumption of atmospheric oxygen for the organic fuel combustion on the planet approaches 40×10^9 t/year and, along with its annual consumption by nature (~165×10^9 t), is greatly in excess of the upper estimation boundary for its natural reproduction (Boldyrev 2016).

Protection of the atmospheric oxygen resources against industrial consumption is currently a top-priority task in regulation of relations between man and nature!

The global ecological crisis the development of fossil fuel power has inevitably led humankind to, offers it no other alternative to have their energy demands met than development of a safe and cost-effective nuclear power (IAEA 2018)! To fulfill its global role, however, nuclear power needs to be of a scale comparable to that of conventional fossil fuel power. As estimated in (Berger et al. 2017), this goal requires nuclear power to have an installed capacity of not less than 10 000 GWel by 2100.

More than that, the progress achieved, e.g., through the electrification of transport, if to be based on conventional fossil fuel power plants, will only worsen substantially the situation with the greenhouse effect and oxygen burning.

The International Energy Agency (IEA OECD), when discussing this issue more specifically at a high-level meeting in July 2018, came to a conclusion that the required level of the NPP capacity would need to be tripled by 2050 by introducing additionally some 1000 GWel to cover 25% of the global nuclear electricity generation (IAEA 2018).

To be reached, such capacity requires a basically new level of nuclear and radiation safety and non-proliferation safeguards and education of professional staff and the population as the whole.

Technology is known to evolve in accordance with Grosch's law, which states: "if a technical system is improved based on an unchangeable scientific and technical principle, then the cost of its new models grows in proportion to the square of its efficiency as a certain level of its evolution is achieved" (Boldyrev 2016).

4.6 Education and training

No less challenging task for younger generations of experts and our society as the whole is cultivation of a new mentality in the humanity that has entered the nuclear era (Figs 10, 11).

Unfortunately, the market priorities of the current nuclear power industrial evolution stage (at least in the countries holding leading positions in this industry – the donor countries for the nuclear technology development, including Russia as well) do not contribute to training of creative and critically thinking highly skilled experts (something the statement above calls for). Market has monopolized the design, development and construction of practically only one type of nuclear reactors for NPPs (95% of the NPPs under construction use water-cooled water-moderated reactors), which explains the fact that single-skilled personnel are largely trained for the construction and operation of this NPP type.

It can be said that nuclear industry has embarked on **capitalizing the reactor science prematurely**, not evolving it to the full extent, at a too "infant" age. We are in haste and squeeze nuclear power into the "locomotive-era" level of thermodynamics getting and operating

Joint Declaration

"Education is imperative to promote disarmament and non-proliferation and, thus, to achieve a world without nuclear weapons.

Education imparts knowledge and critical thinking to individuals and people. Education can raise the awareness of the public, in particular the future generations, of the tragic consequences of the use of nuclear weapons. Education can also empower individuals and people to make their contribution, as national and world citizens, to disarmament and non-proliferation".

Figure 10. Joint Statement at the Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT 2010) (Murogov 2019).

Joint statement on disarmament and non-proliferation education delivered by H.E. Mr. Akio Suda, Ambassador Representative of Japan to the Conference on Disarmament at the NPT Review Conference in 2010 Meeting of Main Committee I, 11 May 2010

On behalf of the 42 countries – Australia, Austria, Brazil, Bulgaria, Canada, Chile, Colombia, Ecuador, Egypt, El Salvador, Estonia, Georgia, Germany, Greece, Guatemala, Hungary, Indonesia, Iraq, Ireland, Italy, Japan, Kazakhstan, Kyrgyzstan, Lithuania, Namibia, New Zealand, Norway, Mexico, Mongolia, Papua New Guinea, Peru, the Philippines, Poland, Portugal, Uruguay, the Russian Federation, Samoa, Sri Lanka, Sweden, Switzerland, Thailand and Tonga.

Figure 11. Statement at the Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT 2010) (Murogov 2019).

- It seems to me that the presented materials point to a bright future of nuclear power even if following a well-worn path, taking, as the basis, the known thermodynamic cycle developed for and adapted to combustion of conventional fuels, such as coal, oil, etc. It is only natural **to anticipate that energy cycles to meet to a fuller extent the specific features of nuclear power generation are the thing of the distant future.**
- **Throughout his field, scientists and engineers will have prospects of a major, most interesting and promising work.** It can be successfully and rapidly implemented only with a concurrent involvement of scientists from all over the world working in different fields, such as physics, electronics, metallurgy, chemistry, electrochemistry, heat engineeing, etc.
- I believe that time is near when the great discovery, **atomic energy, will not be cursed by humankind but will become an indispensible part of our culture and wellbeing, such as electricity is now.**

Kapitsa

Figure 12. A fragment of P.L. Kapitsa's 1955 paper (Kapitsa 1955).

at the lowest possible parameters in all kinds of power industries (Kapitsa 1955).

Without defining the objectives for the future and without knowing answers and solutions arising retrospectively, we initially build NPPs and, then, e.g., as a grave accident happens, try to develop hastily a **technology to find the way to cope with the problem**. The situation is more complicated with non-proliferation culture.

5. Conclusions

Academician P.L. Kapitsa wrote back in 1955 that new competitive NPP units cannot be built without changing the scientific and technical principle of atomic energy conversion to electrical energy (Fig. 12) (Kapitsa 1955).

Achieving a full-scale evolution level of nuclear power capable to cope with socio-economic and environmental issues, the challenges faced by humankind, requires a basically new evolution concept of nuclear power (Kapitsa 1981) and its nuclear fuel cycle (Bashkirov 2018). No less challenging objective of our society is to cultivate a new mentality in the humankind that has entered the nuclear era.

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