УДК 621.039

To centenary of I.V. Kurchatov,
A.I. Leipunsky and A.P. Aleksandrov birth

NUCLEAR POWER: STATUS, OUTLOOK, GUARANTEES OF SUSTAINABLE DEVELOPMENT

A.S. Cherkasov
Kharkov National University, Ukraine, 61077, Kharkov, pl. Svobody, 4
Received October 1, 2003

The principal advantages of nuclear power – almost unlimited fuel resources, its high energy capacity, ecological compatibility with a possibility of high wastes` concentration – determine the large-scale nuclear power development. The signs of large-scale power – a large rate (dozens of percent) in electricity production, diverse areas (electricity, heat supply, technologies, transport) and media of application (land, ocean, space), extension of number of user countries, diversified power systems (centralized, autonomous), obligatory reproduction and reuse of produced fuel – create various requirements to nuclear power installations of the future. Economic efficiency and competitiveness, safety (of reactors and fuel cycle with waste), proper characteristics of nuclear fuel reproduction, guarantees of nuclear arm's non-proliferation and, particularly, public acceptance are the conditions of such nuclear power development. The up-to-date situation is the following: the 441 nuclear power-generation units with total installed power of 377.36 GW el. (in 31 countries) supply by 1/6 part of the world electric-power consumptions. The 32 units are in stage of the construction. To the present mid-century the level of the nuclear power production, as supposed, must be increased 4–5 times at the following scenario of a regional distribution of nuclear electric powers, GW: USA, Europe and developed countries of Eastern Asia – 1000, FSU-countries – 100 and developing countries – 400.
KEY WORDS: nuclear power, status, fire power, competition, outlook, principal advantages, innovative designs, safety, efficiency, public acceptance, global energy supply.

Today, as in the time of the nuclear pioneers, civil nuclear energy faces a paradox. Its advantages and its potential to play a key and growing role in the global energy supply are clear and obvious. Nuclear power has no alternatives associated with a growth of a "clean" electric power production (to the present mid-century the nuclear power production level must be increased, as supposed, 4-5 times at the following scenario of a regional distribution of nuclear electric powers, GW: USA, Europe and developed countries of Eastern Asia – 1000, FSU-countries – 100 and developing countries – 400 [1]), with a preservation for posterity of very valuable raw material sources (oil, natural gas), with a prevention of climatic changes, with ensuring of the energy safety in some countries in which sufficient own power resources are absent, and, finally, with ensuring of the astronomical safety for the Earth from asteroids in diameter more 50 m (it will be need of nuclear explosions or of low-thrust nuclear-fission (or fusion) rocket engines with a long-term operation). To viewing the matter in the political aspect the nuclear weapon continues playing the role of a constraining factor. Nuclear power technologies are especially effective for power-intensive productions removed from the basic power system (for remote locations).

However, today modern nuclear power, as it is an alternative energy source, develops in conditions of radiophobia (after explosions of atomic bombs and the Chernobyl accident) and, it is said, of the ecological extremism that is associated, in the main, with concern of society by the solution of problems which were accumulated during 50 years of its existence and also with a safety of nuclear industrial installations as possible objectives for the terroristic actions of the mass frightening. These near-term obstacles are so important that could cause much of its potential to go unrealized at all. We must focus on these obstacles and address them efficiently.

For all that modern nuclear power (nowadays, the 441 nuclear power-generating units in 31 countries with total installed power of 377.36 GW el., the 32 units of 26.84 GW el. are in the stage of a construction) – in the cut-throat competition with traditional and updated fire power on organic fuels, particularly, with high-efficient steam-gas (CCGT-combined cycle with gas turbine) and dust-fuelled coal (ESP) heat power plants – supplies 1/6 part of the world power consumption. In 2001 all NPP's (Nuclear Power Plants) produced the record quantity of electric power about 2600 TW-h that is, approximately, on 150 TW-h more than in the previous year [2]. In 2002 it was produced 2665 TW-h (in the USA – 780 TW-h; in Russia – 140 TW-h, the 10 NPP's, the30 units of 22.26 GW el.; in Ukraine – 78 TW-h, the 13 units of 11.8 GW el.). The commercial operation of NPP's in 2002, as in the previous year, is equivalent to the decrease of carbon dioxide ejections in the size of 2.7 billions tonnes that is about 10% of the annual emission of this atmospheric contamination [3]. An operation experience of power reactors achieved to the present day about 10700 reactor-years. NPP's are making a reliable and cost-effective contribution to the supply of energy. The technical reliability of NPP's worldwide is reflected by high plant availabilities of , on the average, 83%, as well as in the low-cost generation of electricity associated with it [4]. The well managed NPP`s on the liberalized and supersaturated market of energy sources are competitivable and profitable dealings. In 2002 in Russia the mean heat power plants' charge was of 40.1 cop./kW-h whereas the NPP's charge was of 38.8 cop./kW-h. Price-redoubling for natural gas, which will happen in any time as previous experience of international hydrocarbon markets shows, will add from 70 to

80% to the cost of production of electric power by gas turbine with combined cycle. On the other hand, price-redoubling for uranium, that is highly improbable at existent conditions on the uranium markets, would increase the cost of nuclear electric power only by 5% [4]. From the end of the 1980th the stable decrease of an occupational exposure is observed at NPP's and at fuel cycle plants [5]. The focus of most industrial activity today is on improving the performance of existing NPP's designs, improving capacity factors (in successful case that will be able to give additionally about 100 TW-h el.) and extending lifetimes [6] as more than the half of operated NPP's in the world worked less twenty years [4]. The additional 5.5 GW el. will be able to give the modernization of eighth Canadian NPP's which are stopped now. The decision by Finland to build its firth nuclear power plant also underlines the positive assessment of nuclear power [3].

Power development in the XXI century will follow the trend to more uniform consumption per capita and per region. The hydrocarbon fuel will continue to serve as the main energy source in nearest decades. According to the forecast of the World Energy Counsel by the year 2020 the power consumption must be increased, as minimum, by 50% (more than for whole XX century) and its part in the consumption of primary resources will stay at the level by 90% because of be all infrastructure of modern production and consumption of energy is oriented to this fuel [1]. That is why every year updated IAEA pessimistic (low) projection is a 9% decrease in global nuclear electricity production by 2020 [7]. This assumes no new nuclear plants beyond what is already being built or seriously planned today, plus the retirement of old nuclear plants. The optimistic (high) projection is for a 53% increase in nuclear electricity production by 2020. This assumes policy changes favorable to nuclear power in some industrialized countries and more success in nuclear developments in developing countries.

If you look at longer term scenarios, e.g., such as those published in 2000 in the Special Report on Emission Scenarios by the Intergovernmental Panel on Climate Change, most of them project significant nuclear growth above that in the previous high scenario with continuing growth beyond 2020 all the way 2100. According to the International Energy Agency data by the year 2020 an electric-power production will be increased by 75% (CO_2 emission – about 60%). The main peculiarity of the 21st century is a very large forecasted increase in population and energy consumption in the developing regions (Asian Pacific Region particularly) – more than 2 and 8 times respectively by the year 2100 compared to the year 1990. For the rest regions of the world this increase is 12…15%. Thus world consumption of end-use energy increases 3.5 times. It requires, of course, appropriate energy developing and creates serious economic, ecological, social and political problems.

The long term scenarios assume that continuing R&D will lead to continuing cost reductions and performance improvements for nuclear power technology. (The assumption that the performances and costs of NPP's will continue to improve, like other technologies, is probably right, but that improvement will not happen by itself. It requires action and investment [7]. In the long term, continued progress will depend on innovative new designs. This will require support by governments, both individually and co-operatively). Apparently it takes into account and that mastering deposits of the hydrocarbon fuel are being depleted, that is in future more investment will require and, accordingly, the prices will increase. A powerful global factor to constrain fire power is the contamination of environment. The scales of problem of decreasing of emission of a hotbed gases and other noxious ejections are very large. For instance, to preserve the CO_2 ejections in the electric power industry on the level of middle of past century – soon after XX century will require a tenfold increase of electric power sources which are not connected with carbon ejections [1]. The problem is very difficult if takes into consideration that the hydraulic power engineering has limited potential of a growth. The technological directions to solve this problem are obvious: the increase of an efficiency of production and of use of electric energy; the use of renewable energy sources besides of a hydraulic power engineering (at the present such-like renewable energy sources produce of $116 \cdot 10^3$ MW el., and by 2013, it is to be expected, will be of $300 \cdot 10^3$ MW el.); the development of nuclear technologies (fission and fusion; in contrary to renew energy sources nuclear power is characterized by an unique economy and a very small sensibility to the weather conditions); the insulation of carbon that will permit potentially to increase the use of coal.

The world today faces several serious crises caused not only by nuclear weapon-material management but also by population explosion, tremendous poverty and starvation (according to the UN data in the past century the population was increased 3 times, today there are 6.3 billions, by 2050 will be 8.9 billions; more 800 millions of an able to work people are unemployed), the lack of fresh drinking water and food (in past century the demand in fresh water is increased 17 times, today more 1 billion people have no the high quality fresh water (by the year 2025 2/3 of whole population is expected to suffer to the same fate), every of the six men is living from hand to mouth, about 1 billion people are inhabiting in the slums). The world faces large gap in domestic power consumption of Western and developing countries, environment problems included and the heat contamination (to the end of present century the average temperature, as supposed, may be increased on 7-8^{0}C – the most pessimistic long term projection), an impetuous increasing of natural, technogenic and ecological accidents-catastrophes. In 1995-1999 an average annual quantity of catastrophes is increased almost 3 times in comparison with 1965-1969 [8]. The calculations show that already by the middle of the century all efforts on the growth of the world economy will level by the natural and technogenic catastrophes. The important role in growth of quantity of natural accidents plays, as supposed, a global climatic grow warmth. In this connection, the public safety has been put in the forefront. In the 21st century it is expected the further separation of the population for the poor ("South") and the rich ("North"). It will provoke international tension with serious conflicts. In the 21st century it is expected aggravation of social contradictions, increase of confessional, ethnic, national aggression and international terrorism.

To solve such issues, we can not simply incinerate weapon-head materials, and a new rational nuclear energy technology should prepare a huge, safe (no severe accidents), nuclear proliferation resistant (anti–terrorism) and economical Nuclear Energy Industry in present century. That is why R&D and new experimental designs have to begin in the nearest future as in the long term, as mentioned early, continued progress will depend on innovative new designs in nuclear power technologies.

The key factors – guarantees of the inevitable large–scale development of nuclear power may be formulated so [9,10,11]:

1. A stable sustainable global increasing in the consumption of electric power and in the power supply (as well known, an every additional per cent of an electric power production per capita leads to increasing of gross output by 3% approximately).
2. A depletion of organic fuel resourses (mainly, oil and natural gas) and, accordingly, a raising of their prices.
3. A lack for proper power resourses in many countries (e.g., in Western Europe [12]) and a necessity of their uninterrupted import for ensuring of the energy safety, that is the rising of the priority in the power supply, particularly, in the Asian Pacific Region.
4. Introduction of global restrictions on the emission of hotbed gases and regional limitations on other air pollution with the introduction of harder economical sanctions at the same time against of countries which are not carried out these requirements, e. g., in respect of the USA which refuses to ratify the Kioto’s convention 1997 (a part of the USA in the total hotbed gas emission is of 36-43%, of the European Union > 24%, of Russia > 17%, of Japan > 8%).
5. In going to the hydrogen power and nuclear seawater desalination by means of high temperature nuclear reactors that have to exclude from the oil import.
6. The innovative designs of simple, standardized, modular, many-functional, with high efficiency and inherently safe, self-adjustable – natural safe and acceptable final cost nuclear power-generating units with the comparatively low power (up to 100 MW el.) that have to permit quickly and with comparatively small investments to construct the NPP’s of different necessary sizes and powers with an acceptable cost of the electric-power production for the modern competitivable market, including modular high temperature reactors for incineration of ex-weapon-grade plutonium and also graphite reactors with unlimited term of their operation for the district heating, conversion of organic fuels, hydrogen production and seawater desalination for the developing countries [13,14]. The “Generation IV “ International Forum Counsil (GIF – Argentina, Brazil, the United Kingdom, Canada, the USA, France, South Africa, South Korea, Japan, Switzerland) chose the six reactor concepts for co-operative R&D over the power range 150…1500 MW el. and with the term of the realization up to 2030: LFR –- Lead (or PbBi)-cooled Fast Reactor, MSR – Molten-Salt Reactor, FSR – Fast Sodium Reactor, SCWR – Supercritical Pressurized Water Reactor, GFR – Gas-cooled Fast Reactor (each reactor with closed fuel cycle) and UHTR – Ultrahigh-Temperature Reactor (an open cycle). In the context of new millennium the international collaboration is very important for the successful renaissance of nuclear power. The union of the resources, share a resource and a performance of joint capital-intensive or labors-consuming intensive researches not only decreases expenses for each country-participant but also opens possibilities of the creation of more dynamic multinational scientific groups.
7. An improving of service property of nuclear fuels, innovative designs of new fuels with the use of U, Pu, Th (the long-term operation of NNP’s is possible only on the basis of ^{238}U+Pu and ^{232}Th+^{233}U – fuels) with the high burnup (on the basis of ThO_2, the use of inert matrix, nitride, MOX (UO_2+PuO_2, UN+PuN), composite, ceramic fuels and microfuel – the using of small spherical fuel particles with the protective coating, and etc.) that ensures a high degree of the protection from arm’s proliferation of fissile materials and a high level of ecological safety of NPP’s. (Microcartridges are very small, spherical, in diameter up to 1 mm fuel particles which are placed into multiple-walled, high temperature and very stable ceramic envelope which is able to provide the effective fission-product retention at the temperature up to 1600°C. An application (implementation) of such microcartridges will allow to create reactors with unique virtues of safety relative to any major accidents including those that are caused by diversions or operations of operating personnel. The fission-product and fuel retention within of protective envelopes at major accidents is the key problem of NPP’s safety).
8. An increase of the regime flexibility of the NPP’s operation, the cost reduction of a management, checks and monitoring of the NPP’s operation, the solution of question of responsibility (nuclear liability). Apparently it is time for transition to so-called guaranteed safety (exclusion of major accidents and insurance of the nuclear damage) [15]. The insurance of civil responsibility with respect to nuclear power objects it is possible to consider as “an external factor” for improvement of their safety (proposed of engineering solutions) because of supervision of insurers who must to look after their own interest. Development of insurance of catastrophic risks permits to improve social atmosphere in regions where the nuclear- and radiation-dangerous objects are disposed (in the stage of a selection of a construction site, of a service and a removal from the service of such objects) [16].
9. Acceptable solution of the problem of a storage and utilization (conversion) of ex-weapon grade uranium and plutonium (“change of megatonnes in megawatts”), processing of spent nuclear fuel (which must be considered as a

perspective basic material of a nuclear-power complex), its partitioning and transmutation (P&T) [17], and also the long-term ecologically safe storage and the final disposal – the burial of the radioactive waste in underground long-term disposals (a geological isolation), radioactive decontamination, and a removal from the service of NPP's and other installations, a rehabilitation of contaminated areas and territories.

10. A creation of the cleanest, most effective, with low-level processing wastes, and the most resistant to the proliferation of fissile materials of technology of the closed fuel cycle. (A well organized closed fuel cycle has the less proliferation risk than the open one. In the open cycle the long-term keeping of irradiated fuel decreases its radiation barrier that lightens its possible processing for production of plutonium. So it is simplified the weapon use of such materials. There are also other problems on the way of direct disposal of spent fuel. That is why in many countries a maratorium was put into effect on this technology of the completion of the nuclear fuel cycle). Nuclear power is an unique industry in which the waste are collected and supervised very carefully. The accumulation of spent fuel is the world-scale problem. At the present, about of 200 thousands tonnes are accumulated. It is necessary to create the International Center for storage, processing, utilization of spent fuel and manufacture of a new fuel. It is necessary to minimize the quantity of radioactive waste (for the final disposal) in these processes.

11. A perfection of non-proliferation and a physical protection (safeguard) of fissile materials (account, inspection, monitoring, a reduction of accumulations and stores, etc.), a creation of a complex system for safeguard, a computer supervision, an account of nuclear materials, and the systems of remote monitoring for NPP's and other installations of a fuel cycle that ensures great extent of the protection from terrorism and radiological weapon, particularly, from the "dirty" bomb.

12. Formation in society (which thinks of nuclear fuel cycle facilities, in the main, as the source of the increased hazard) scientific and technical notions about atomic nucleus and radiation, and about everywhere penetrative radiations as a form of material world, about that that absolute safety is absent, unfortunately, but that a safety is a normalized and acceptable danger. It is need of "public understanding" (in terminology of Academician V.I. Vernadsky) of nuclear industry, of a formation its image as an industry of XXI-st century.

13. A stable and safe (no severe accidents) function of all radiation objects. Ensuring of the culture of safety as the highest priority of safety at performance of nuclear- and radiation-dangerous operations that is an education for operating personnel of responsibility relative to any their operations at NPP's and recognition and realization of the possibility to cause damage to society (population) and environment on account of incompetent and erroneous operations.

14. A struggle with the antinuclear extremism and populism of the number of the politics who hide, as a matter of fact, from the society the severe consequences and the great losses were caused damage to the society in the result of the political and managemental errors.

Economic competitiveness and public acceptance are the most vital factors for the growth of nuclear power. Public acceptance will depend on the continuing strong emphasis on nuclear safety, acceptable solutions to spent fuel and radioactive wastes disposal and a globally accepted non-proliferation nuclear weapon regime. Of great importance in the formation of a positive attitude of the society to the future of nuclear power engineering may be the popularization of the concept of the nuclear fuel cycle based on the use of technologies, which exclude deterministically the possibility of severe radiation accidents, and provide the ecological balance of radionuclides in the biosphere in the radioactive waste management. A new era comes – this is era of nuclear energy characterized by a higher level of safety, more improvemental technology of the waste reduction, more improvemental service properties, as well as by higher degree of a nuclear weapon defense (with a point of view of non-proliferation of the nuclear weapon). The key technical problems are determined. The principal ways of the solution of these problems are known. As a matter of fact, it is the problem of the sustainable development of our civilization.

REFERENCES

1. Пономарев-Степной Н.Н., Кузнецов В.В., Гагаринский А.Ю. и др. Будущее ядерной энергетики: энергия, экология, безопасность. – Атомная энергия.– 2002. – Т.93.– Вып. 5.– С. 327– 342.
2. Информация (ATW, 2002, v.47, H.4, s. 263–269). Эксплуатация АЭС, 2001.– Атомная техника за рубежом, 2002, № 8. – С. 32.
3. Митяев Ю.И. Ядерная энергетика в 2002г.– Атомная техника за рубежом, 2003, N7.– С.11–13.
4. Echavarry L. Nuclear energy in Future sustainable, Competitive Energy Mixes.– ATW, 2003, Jg.48, H.1, s.18-27.
5. International Atomic Energy Agency (IAEA) and Nuclear Energy Agency (NEA) Occupational Exposures at Nuclear Power Plants: Tenth Annual Report of the ISOE Programme, 2000, OECD, Paris, France.
6. Rogner H.H., Langions L.M., McDonald A. Nuclear Power Status and Outlook.–Atomwirtschaft–Atomtechnik, 2001, Jg. 46, № 12, s. 762–766.
7. Mourogov V.M. Role of Innovative Nuclear Technologies for Sustainable Development and IAEA Activities.–Abstracts of Nuclear Society of Russia 13-th Annual Conference "Environmental Safety, Technogenic Risks and Sustainable Development", 23–27 June, Moskow, p. 16–19.
8. Осипов В.И., Динамика риска природных катастроф.– Ihid., с.5–8.
9. Shuppner S. DoE initiatives to Advance Nuclear Energy in the United States.– ATW, 2002, Jg. 47, H. 3, s. 158–161.
10. Abraham S. Generation IV International Forum 2002, Remarks.– ATW, 2002 , Jg. 47, № 11, s. 678–680.

11. Солонин М.И. Состояние и перспективы развития ядерной энергетики России.– Атомная энергия. – 2003. – Т. 94. – Вып. 1. – С. 31–36.
12. Schmidt –Kuster W.T. The future of Nuclear Energy in Europe.– Atomwirtschaft – Atomtechnik, 2000, Jg. 45, H. 11, s. 688–690.
13. Small reactor return. – Nuclear Engineering International.– 2002.– V. 47, № 579, P. 24–25.
14. Маэкава Н. Исследования в области создания реакторов малой и средней мощности. – Атомная техника за рубежом. – 2001, № 3.– С. 32–33.
15. Осмачкин В.С. Безопасность ядерной энергетики в 21 веке. – Сборник материалов 14-ой ежегодной конференции Ядерного Общества России "Научное обеспечение безопасного использования ядерных энергетических технологий", Удомля, 30 июня–4 июля, 2003, с.58–62.
16. Воронов Д. Б., Прохоров В. Г., Гаврилов С.Д. и др. Страхование ядерных и радиационных рисков в России как внешний фактор обеспечения безопасности персонала и третьих лиц. –Сборник материалов 14-ой ежегодной конференции Ядерного Общества России "Научное обеспечение безопасного использования ядерных энергетических технологий", Удомля, 30 июня–4 июля, 2003, с.87–92.
17. Махова В.А., Соколова И.Д., Шульга Н.А. Исследования по фракционированию и трансмутации долгоживущих радионуклидов. – Атомная техника за рубежомю– 2003, № 3.– С. 3–10.

ЯДЕРНАЯ ЭНЕРГЕТИКА: СТАТУС, ПРОГНОЗ, ГАРАНТИИ УСТОЙЧИВОГО РАЗВИТИЯ

А.С. Черкасов

Харьковский национальный университет, Украина, 61077, Харьков, пл. Свободы, 4

Принципиальные положительные качества ядерной энергетики – практически неограниченные ресурсы топлива, его высокая энергоёмкость, экологическая совместимость с возможностью высокой концентрации отходов – предопределяют развитие крупномасштабной ядерной энергетики. Признаки крупномасштабной энергетики – большая доля (десятки процентов) в производстве электроэнергии, разнообразные области (электроэнергетика, теплоснабжение, технологии, транспорт) и среды применения (суша, океан, космос), расширение числа стран-пользователей, различные энергетические системы (централизованные, автономные), обязательное воспроизводство и повторное использование наработанного топлива – создают разнообразие требований к ядерно-энергетическим установкам (ЯЭУ) будущего. Условиями развития такой энергетики являются её экономическая эффективность и конкурентоспособность, безопасность (реакторов и топливного цикла с отходами производства), достаточные характеристики воспроизводства ядерного горючего, гарантии нераспространения ядерного оружия и, особенно, общественная приемлемость ядерной энергетики. Современная ситуация характеризуется следующим: 441 ядерных энергоблоков с суммарной установленной мощностью 377,36 ГВт эл. (в 31-ой стране) обеспечивают 1/6 часть мирового потребления электроэнергии. 32 блока – в стадии сооружения. К середине века уровень производства ядерной энергии, как предполагают, должен увеличиться в 4–5 раз со следующим сценарием регионального распределения электрических мощностей, ГВт: США, Европа и развитые страны Восточной Азии – 1000, страны СНГ – 100 и развивающиеся страны – 400.

КЛЮЧЕВЫЕ СЛОВА: ядерная энергетика, статус, огневая энергетика, конкуренция, прогноз, принципиальные преимущества, инновационные разработки, безопасность, эффективность, общественная приемлимость, глобальное энергоснабжение.