NUCLEAR POWER OF THE COMING CENTURY AND REQUIREMENTS TO THE NUCLEAR TECHNOLOGY

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ABSTRACT

Current state of nuclear power in the world has been considered and the reasons for its falling short of the great expectations relating to its vigorous development in the outgoing century are considered. Anticipated energy demand of the mankind in the next century is evaluated, suggesting that with exhausted resources of cheap fossil fuel and ecological restrictions it can be satisfied by means of a new nuclear technology meeting the requirements of large-scale power generation in terms of safety and economic indices, moreover, the technology can be elaborated in the context of achievements made in civil and military nuclear engineering. Since the developing countries are the most interested parties, it is just their initiative in the development of nuclear technology at the next stage that could provide an impetus for its actual advance. It is shown that large-scale development of nuclear power, being adequate to increase in energy demand, is possible even if solely large NPP equipped with breeders providing BR ≥ 1 are constructed. Requirements for the reactor and fuel cycle technologies are made, their major aspects being: efficient utilization of Pu accumulated and reduction of U specific consumption by at least an order of magnitude, natural inherent safety and deterministic elimination of accidents involving high radioactive releases, assurance of a balance between radiation hazard posed by radioactive wastes disposed and uranium extracted from the ground, nuclear weapons nonproliferation due to fuel reprocessing ruling out potentiality of Pu diversion, reduction of the new generation reactor costs below the costs of today's LWR.

I. INTRODUCTION

The doubling of the global population expected by the mid-century, mostly due to the developing countries, and the ever-increasing number of nations taking the course of industrial development are bound to cause at least doubling of the world's demand for primary energy and trebling of the demand for electricity.

The growth of energy production will be in all probability accompanied by gradual depletion of cheap hydrocarbon reserves and by a rise of their prices. The world fuel market is likely to be increasingly affected by the endeavors of various countries to preserve their national hydrocarbon resources as a chief item of export, for many of them, and as fuel for transport and raw materials for chemical synthesis.

The looming hazard of international conflicts around oil and gas sources is another factor to be reckoned with.

Use of fossil fuels, including huge coal resources, can prove to be closer to its end than is currently expected, on account of the emissions of combustion products and global climatic changes. Besides the rise of fuel prices, measures taken to minimize harmful releases are bound to add to the capital costs of the energy sector.

The main provision of the long time reliable energy supply would be the development of new energy technologies capable of large-scale and economical replacement of fossil fuels.

With half a century of practical experience behind them, fission reactors might seem to be an eligible and realistic alternative to the conventional energy sources. But deployment of thermal reactors fueled with ^{235}U is limited by the resources of cheap uranium reactors are assessed at somewhat more than 10^7 t, which in terms of the energy equivalent is less than the estimated resources of oil and gas, let alone coal. This means that ^{235}U-fueled reactors are incapable of having a greater effect on the global consumption of conventional fuels. With its current share in electricity production, nuclear power based on traditional reactors, mostly LWRs, can go ahead for another ~40 years to supply the demands of fuel-deficient countries and regions. Nuclear power can be deployed on a much larger scale, using fast reactors - which only some 20 or 30 years ago was believed attainable within this century. However, contrary to expectations, the first generation of fast reactors proved to be much more expensive than LWRs. It is only to be regretted now that the root causes thereof were never brought to light - with the result of an ingrained prejudice against fast reactors stamped as inevitably costly machines. The hazard of proliferation of nuclear weapons is also associated with fast reactors and the closed fuel cycle.

For these reasons as well as the grave accidents at TMI and Chernobyl, energy saving measures and others the expected large-scale deployment of nuclear power was never brought into effect, deferred till some not entirely definite time in the future.

2. ENERGY TECHNOLOGY OF THE NEXT CENTURY

Meanwhile, studies show that it is possible to create a nuclear technology which will meet the safety and economy requirements of large-scale power production without going too far from the achievements of civil and military nuclear engineering. If in the next few years, the States concerned recognize the vital need for resolving the problem, and doing so in good time, and if they succeed in adopting a definite concept, the engineering development and demonstration of the latter can be carried out within a reasonable period of about 20 years. Thus the stage would be set for a new nuclear power which in the next century could take on a major part - say, half - of the increase in the global demands for fuel and energy. This means that nuclear power should grow by an order of magnitude from its present-day level of ~340 GWe by the mid-century and then double or treble its capacity before the end of the century.

Nuclear technology development has long since acquired the traits of an international effort and in the century to come will be guided by the global energy requirements, with countries concerned joining forces to carry it on. In so far as such a need is now greatest in the developing countries, it is their initiative in developing a nuclear technology for the next stage that can really give a practical turn to this work.

Such an initiative would undoubtedly find support with Russian nuclear experts whose vast experience and capabilities are currently in poor demand in the country, as well as with specialists from other countries seeking applications for their expertise.

Creation of a new nuclear technology would also answer the fundamental needs of industrialized nations and ought to be supported by their governments with the understanding that this technology would not add to the risk of a sprawl of nuclear weapons.

The criteria for adopting a nuclear technology for the next stage stem from the fairly general view of the future nuclear power discussed below.

3. LONG-TERM SCENARIO OF NUCLEAR POWER DEVELOPMENT

A long-term scenario of nuclear power development, which is of course a most tentative job, is presented in Fig.1. Curve 1 describes the continued advancement of nuclear power on traditional thermal reactors with ^{235}U fuel - mostly LWRs.

Consuming ~200 t of natural uranium a year per 1 GWe and given ~10^7 t of cheap uranium, LWRs will have a total output of ~$5 \cdot 10^4$ GWe·yr, with their operation in reactor-years making roughly the same figure, and will produce ~10^4 t of fissile Pu (~200 kg/yr. per 1 GWe). Reuse of Pu, recovered now at the facilities built in France, UK and Russia, could increase the fuel resources of thermal reactors by 20 to 25%. But the low cost-effectiveness of using MOX fuel in these reactors offers no incentive to expansion of these facilities, while the spread of this technology in the world would add to the hazard of proliferation of nuclear weapons. Pu burning in thermal reactors, which has a low efficiency, would constrain or even bar the way to large-scale deployment of breeders at the next stage. That is why this scenario assumes that the thermal reactors of the first stage will continue operating mostly in the open fuel cycle.

Thermal reactors of different types are most likely to find application in a longer term as well, owing to their advantages in some areas of energy production: small and medium nuclear plants (tens and hundreds of MWth) are well suited to meet local heat and electricity needs of remote regions where construction of transmission lines and fuel delivery are difficult and costly, or to provide high-grade heat for some processes. But to do so, thermal reactors will subsequently have to shift to the Th-^{233}U fuel cycle and a BR of ~0.8 to 1 (curve 2), with the ^{233}U deficit covered by breeders.

But centralized electricity production at large NPPs (of GWe capacity), with power transmission over hundreds of kilometers to regions with a million-size population, will in all probability remain the main sphere of nuclear energy application. Electricity is still the most universal and convenient form of energy, well suited for transmission and final uses; its generation grows at the quickest rate and will account for the predominant part of fuel consumption in the next century (its current share being roughly 1/3).

The experience with high-voltage transmission lines amassed in Russia among other countries and the anticipated advent of economical superconducting lines in the next century, open up possibilities for transmitting electricity from large NPPs over thousands of kilometers and for expanding its export. The trend toward miniaturization observed in other industries is opposed here by the indivisibility of the technological process and by the increase in specific costs with reduction of power, especially for NPPs.

Electricity being a standardized and universal product, changes in the market demand do not entail reorganization of the production process, which together with the ease of long-distance transportation is another point in favor of large power plants and reactor units. This does not preclude the use of nuclear energy for heat supply, while utilization of waste heat from NPPs remains an important problem yet to be solved.

On these grounds, large-scale nuclear power deployment, represented by curve 3 with a conventional start in 2020, is assumed to involve construction of mostly large NPPs. Such a scale can be provided only by breeders with $BR \geq 1$.

An essential objective of this stage is the cost-effective and safe utilization of Pu produced both by the reactors of the first stage (10^4 t) and as a result of nuclear arms reduction (possibly over 200 t). With the use of Pu, $BR \geq 1$ is attainable only with fast reactors, which predetermines their principal role at this stage.

One of the main reasons for using light-weight and heat-conducting sodium as a coolant in the first fast reactors, was its capability to remove high heat fluxes from the fuel, with a resultant decrease in the fuel inventory and in the Pu doubling time, T_2. In the post-war decades, the annual rate of energy production growth reached 6 to 7% (up to 12% in the USSR) and short doubling time, T_2, was regarded as an important criterion in fast reactor development. Along with high power density, another associated requirement was a high breeding gain ($BR \sim 1$), for which purpose a uranium blanket was provided. Studied as long-term options were high-density and heat-conducting fuels, such as metal alloys, monocarbides and mononitrides, which afforded a simultaneous rise in the BR and the power density.

The situation is considerably different now. The growth rates have dropped (a threefold increase of electricity production over slightly more than 50 years corresponds to an average rate of ~2% a year), Pu is building up in large quantities, so short T_2 is no longer needed. The scenario depicted in Fig. 1 can be fulfilled by fast reactors with BR~1 and moderate power density. The 10^4 t of Pu and ~$1.5 \cdot 10^4$ t of ^{235}U in the spent fuel of the first-stage reactors allow bringing in fast reactors ~4000 GWe in capacity, using Pu mixed with slightly enriched (1 to 4%) uranium (additionally enriched regenerated fuel of thermal reactors). As nuclear power settles on an even keel, these reactors will move into the ordinary U-Pu cycle. With an optimum CBR of 1.05 (minimum reactivity variations), nuclear generating capacities can reach ~8000 GWe due to Pu breeding in the early 22nd century. Therefore, their development should be governed exclusively by the safety and economy criteria. These goals can be met by replacing sodium with a chemically passive high-boiling coolant, eliminating the uranium blanket with assured in-core breeding CBR=BR~1, and using high-density, heat-conducting fuel instead of oxide fuel (for the purpose of attaining CBR~1 and reducing reactivity margins, rather than increasing power density). It will be shown below that these and other measures result in an economically efficient high-power fast reactor with an essentially higher level of safety.

Excess neutrons in a fast reactor without a U blanket in the U-Pu cycle and a high flux of fast neutrons endow fast reactors with the advantage of transmutation of long-lived radionuclides to resolve the problem of radwaste without creating special burners. The equilibrium fuel composition (CBR~1) opens the way for the use of a reprocessing technology which consists basically in rather limited removal of fission products and rules out Pu extraction in this process. Use of such a technology in "non-nuclear" countries would afford a certain degree of their independence from nuclear nations without violating the international nonproliferation regime.

This discussion leads us to the conclusion that the choice of fast reactors in the U-Pu cycle as a basis for large-scale nuclear power, made by its founders back in the 1940s-50s, remains valid in the new conditions as well. But these conditions and the experience amassed call for new approaches to the creation of such reactors.

It was already mentioned above that thermal reactors also have some scope for long-term development in certain fields of power production with a switch-over to the Th-U cycle in the future. With their contribution to the future nuclear power assessed at 10 to 20%, it can be shown that the ^{233}U deficit in these reactors may be covered without too much trouble by providing fast reactors with a small thorium blanket to utilize part of the leakage neutrons.

With breeding well-established and the problems of radwaste settled - mainly through transmutation of long-lived actinides - there seem to be no constraints on the duration of nuclear power operation from the viewpoint of cheap fuel resources and radwaste accumulation. But a complete concept of nuclear development should incorporate, among other things, the final stage with phaseout of NPPs and elimination of large quantities of radioactive material from the reactor inventories. This suggests the need for effective burners without nuclear fuel reproduction, which makes the ongoing quest and studies in this area meaningful. However, even if our hopes for the reasonably early advent of economical and safe breeders do come true, the engineering development of such burners will not be started until some more remote time in the future.

4. REQUIREMENTS TO REACTOR AND TECHNOLOGY, CHOICE OF REACTOR TYPE

4.1. Uranium Consumption

Efficient utilization of stockpiled Pu, reduction of specific uranium consumption by no less than an order of magnitude with no need to provide short doubling time.

High-power fast reactor in the U-Pu cycle, moderate power density, CB=CBR~1, no uranium blanket.

Reactor with CBR~1 should have the power of no less than ~300 MWe. CBR~1 also dictates the use of high-density fuel. For many reasons, UN-PuN fuel appears to be an optimum choice.

4.2. NPP safety

Exclusion of severe accidents which may result in fuel failure and large radioactive releases (fast runaway, loss of coolant, fire, steam and hydrogen explosions).

If the operation period of nuclear power in the next stage of its development exceeds 10^6 reactor-years, the probability of the above accidents should be kept well below 10^{-6} per reactor-year. Probabilities of such a level obtained by PSA methods have neither operational experience (the existing nuclear power has operated for about 10^4 reactor-years) nor convincing theoretical data to support them. PSA techniques are useful for planning safety improvements at NPPs and allow quite dependable predictions related to the near-term nuclear power development, but they are unsuitable for preparing a really strong safety case for large-scale nuclear power.

Therefore, reactors of the next stage should present no risk of such accidents under whatever human errors, failures or damages to equipment and safety barriers, i.e. these accidents should be deterministically excluded owing to the intrinsic physical and chemical properties and behavior of the fuel, coolant and other reactor components (natural safety).

Needless to say, there is no way to avoid radioactive releases in case of total reactor and plant destruction as a result of a nuclear attack or a fall of a large asteroid, and these events should be mentioned in the design documentation as exceptions. All potential accidents in a naturally safe reactor, except for those mentioned above, are treated as design-basis events.

Fast reactors with high-density fuel, operating in the U-Pu cycle, can be designed to have optimum CBR~1, no Xe and Sm poisoning, small power reactivity effect due to the use of fuel with high heat conductivity, and small effect of delayed Np decay, so as to keep the total reactivity margin at the level of $\Delta K_{tot} < \beta_{eff}$ and hence exclude fast runaway under any erroneous actions or accidents in the reactivity control system. Without uranium blanket, a fast reactor has a deeply negative integral void effect. Passive control and cooling elements, feedbacks including large negative temperature coefficient dK/dT, a high level of natural circulation of coolant, prevent dangerous temperature growth under off-normal conditions.

Sodium interaction with air and water, which may cause hydrogen generation and lead to a loss of coolant, and the possibility of a local positive void effect showing up during boiling of this coolant, suggest that it should be traded for another, chemically inert, coolant which boils at a much higher temperature. With no necessity to provide high power density in the core and short doubling time T_2, it becomes possible to use, for instance, the heavy coolant which has been successfully employed in Russian naval reactors, namely PbBi eutectic - or

Pb which is close to the former in all physical and chemical characteristics but for the melting point. Use of Pb settles the problems of the high cost and small resources of Bi, and of volatile ^{210}Po with its high alpha activity, produced from Bi. The problems caused by high melting temperature of Pb (327 °C) can be resolved through the use of proper temperature conditions and reactor cooling so as to stay within acceptable steel temperatures and to exclude blockage of lead paths under off-normal conditions.

The deterministic safety requirement implies that the ultimate design-basis accident (UDBA) - i.e. the accident which covers any event resulting from human errors or multiple failures of equipment, including loss of forced cooling, failure of the scram function, insertion of full reactivity margin, damage to outer barriers such as containment and reactor vessel- should not cause fuel failure and radioactive releases such that would require evacuation of people from the territory around the plant.

Analysis of hypothetical (non-credible) accidents including large rapid reactivity addition, fuel failure and collapse with resultant secondary criticality, has been performed optionally, with a view to obtaining ultimate estimates.

Extreme external impacts leading to destruction of the plant, reactor and its vault, will be mentioned in the design documentation, but their analyses are also optional.

4.3. Radwaste

Any predictions concerning safe disposal of large amounts of radwaste for tens of thousands of years give rise to doubts about the validity of geological and especially "historical" forecasts for such remote future.

These doubts can be removed if the radiation hazard from buried radwaste is brought into balance with that of uranium extracted from the earth (radiation-equivalent radwaste disposal), and this is adopted as a requirement for nuclear technology.

- The requirement can be satisfied in the following way:

  long-lived products of U decay (Th, Ra) can be co-extracted with uranium and then handled together with actinides. This step will also facilitate rehabilitation of U mining areas on completion of the work there;

- U, Pu, and other actinides produced during reactor operation, first of all Am, can be returned to reactor to be transmuted by fast neutrons into fission products;
- radwaste can be subjected to treatment with a view to removing actinides so that it contain only $^{\sim}10^{-3}$ of Pu;
- after cooling, radwaste can be brought into a mineral-like state or some other physical and chemical form not prone to migration in soil;
- radwaste can be buried in naturally radioactive geological formations remaining after U mining, in such amounts that they will be equivalent to extracted U in terms of their radiation hazard.

It should be pointed out that long-lived Np produced in reactors has low activity, and can be dumped untransmuted without disturbing the radiation equivalence. Moreover, if returned to reactors Np adds to the fuel activity since it produces highly active ^{238}Pu and ^{236}Pu which decays to ^{232}U.

Cm, whose main isotopes have a relatively short half life and a high activity, especially neutronics, can also significantly increase fuel activity if returned to reactor for transmutation, thus impeding fuel refabrication. Therefore, it would be better if Cm were separated from fuel during reprocessing, cooled for some 50-70 years and then returned to reactor in the form of decay products, i.e. Pu isotopes.

Attainment of radiation equivalence between radwaste and mined uranium would also benefit from separation of Sr and Cs so that only 1-10% of them will remain in radwaste. Extracted Sr and Cs could then be utilized as radiation or heat sources. Long-lived I and Tc (with 1-10% of them going to wastes), if extracted, can be returned to reactors for transmutation. The remaining radwaste (with the activity of about 10^4 Ci/l) can be stored in casks cooled by dry air under natural circulation. The activity of radwaste stored in this way would fall by three to four orders of magnitude in 200 years, which simplifies the technology of final disposal of radwaste and enhances its safety. Analysis shows that such storages can be designed to be simple and not very expensive.

There would be no problems or risk associated with long-distance transport of radwaste if fuel cycle facilities and radwaste storages were set up on NPP sites.

4.4. Nonproliferation

A fast reactor with CBR$^{\sim}$1 and no uranium blanket operates with fuel of equilibrium composition and has no need for Pu separation or addition during fuel fabrication. To adjust the fuel composition, it is sufficient to add ^{238}U to compensate for its burnup.

This fact allows putting forth the following requirement: reprocessing technology should be such as to rule out Pu separation. In this case, reprocessing will boil down essentially to removing fission products from the fuel. In the context of their influence on reactivity, it is acceptable to remove FPs so that ~1-10% of them remain in the fuel, which would simplify the above technology and facilitate its choice, though increasing the fuel activity, in particular during refabrication. This is not a major complication, however, since the process is remote anyway. Besides, a high activity of fuel is another warranty against its theft.

The main point here is that such a technology will not add to the risk of proliferation and hence may find worldwide application.

Needless to say, there is no way in which any new fuel cycle technology can rule out illegal application of existing techniques of Pu separation, in particular from LWR fuel, or uranium enrichment for the purpose of obtaining weapon-grade materials. This problem can be successfully dealt with only by political steps meant to enhance the nonproliferation regime and improve the safeguards. Moreover, it has to be resolved irrespective of the further route of nuclear power and nuclear technology.

Promotion of the breeding technology appears to be the most cost-effective way of utilizing Pu accumulated in spent fuel from modern reactors. With this option, Pu would be taken from cooling ponds and put into reactors and fuel facilities, which affords maximum safeguarding and reduces the risk of illegal plutonium separation and utilization.

Fast reactors without uranium blanket, with CBR~1 and moderate power density, have many traits and possibilities essential for attaining this goal:

- there is no U blanket to produce weapon-grade Pu and with a small reactivity margin in these reactors, it is no longer possible to put U assemblies in the core for Pu accumulation;
- small reactivity variations during refueling, moderate power density and on-site fuel cycle allow quasicontinuous on-load refueling. Spent fuel can be cooled during 3 to 12 months in an in-vessel storage facility and then sent directly for reprocessing and refabrication. Hence there will be no

need for out-of-pile storages for spent and fresh fuel. Such fuel handling can largely simplify supervision and practically excludes fuel thefts.

Initial reprocessing of spent fuel from thermal reactors and fabrication of first cores for fast reactors will have to be done at facilities available in the nuclear countries, but this dependence will not be so strong as in case of regular supply of enriched uranium. Consideration may be given to setting up nuclear technology centers on the basis of these facilities under international jurisdiction.

The aqueous technology widely used now and other options being studied at the moment, are tailored to existing reactors which require Pu separation. To meet the above requirement, it is necessary to alter the existing reprocessing technologies or to develop a new one, and this is one of the major challenges along with the development of new reactors. Physical methods of fuel treatment, in which FP removal relies on a factor of two difference in atomic weights, may prove to be the most effective and simple solution.

No concept of a closed fuel cycle satisfying the requirements of large-scale nuclear power, has been suggested yet. It will not fail to appear, however, once the objective is properly defined, and then the requisite technology can be developed and demonstrated within the period of the reactor development.

4.5. Economics

With cheap fuel, it is the NPP cost, which has grown considerably during the last years on account of safety improvements, that is largely responsible for the cost of nuclear energy generation. NPPs of the next stage should be cheaper than modern LWRs, to be economically competitive in many countries and regions.

As is the case with most of the sophisticated technological systems, NPP cost is determined by many things. No separate improvement in one area (for instance, use of natural water circulation instead of pumps in BWRs) can reduce this cost by more than a few per cent. NPPs with fast reactors should be made at least twice cheaper, which calls for some basic solution extending to the main equipment, systems and structures, whose high costs stem from safety requirements. The answer in this case comes from the natural safety philosophy.

High safety level of new plants, achieved mostly owing to elimination of potentially dangerous design solutions and due to the use of the laws of nature, will make it possible to simplify plant design, lower requirements for basic and auxiliary systems, structures and personnel, and will obviate the need for additional safety systems. These potentialities can be translated into plant design based on consistent application of the natural safety philosophy.

5. AN EXAMPLE OF A NATURALLY SAFE FAST REACTOR

The conceptual design of a fast reactor with UN-PuN fuel and lead coolant (BREST), developed not so long ago, proves that it is possible to meet all the above requirements keeping to a proven technology.

Design and analytical studies were performed and then optimized for reactors with the power in the range from 300 MWe to 1200 MWe. Experiments carried out at U-Pu-Pb critical assemblies sought to validate reactor physics and revise the nuclear data. Steels were subjected to long-term corrosion testing in Pb circulation loops. Experiments were performed to study Pb interaction with air and water of high parameters, interaction of nitride fuel with Pb and steel claddings, and other things.

Calculations on the ultimate design-basis accident, as it was defined above, showed that this reactor can survive it without fuel failure and with moderate radioactive releases. Investigations into hypothetical accidents confirmed that the reactivity addition of up to several β_{eff} at a rate of up to 50 β/s does not cause lead boiling and large release of mechanical energy. According to these studies, lead density, which is close to that of fuel, and convective flows prevent fuel collapse which may otherwise result in the formation of a secondary critical mass.

Lead-cooled fast reactor has a simpler design than LMFR-Na:

- single vessel or pool-type arrangement without a metal vessel (reactor is placed directly in a concrete vault with thermal insulation between concrete and lead);
- two circuits in the main and emergency cooling systems; decay heat removed by natural circulation of air in tubes located in the lead coolant of the primary circuit;
- no special system to wash coolant off FAs during refueling;
- reactivity control provided mostly by lead in tubes located in the side blanket; lead level in tubes is regulated by gas pressure;
- passive control and protection features with threshold response; high level of natural circulation of coolant; less stringent requirements to the speed of operation with simplification of control and protection systems;

- simpler design of steam generators, with no need for fast-acting leak detection systems and quick-response valves;
- less sophisticated fire protection, ventilation and other support systems and components; simpler rooms in the cooling circuits and other NPP constructions.

Cost estimations and comparisons confirm that it is possible to reduce capital costs of such NPPs and the cost of their electricity, as compared to those at VVER plants.

Operating experience of reactors with a heavy coolant, extensive in-pile testing of nitride fuel, calculations and experiments performed in the course of the conceptual design, made the basic aspects of the concept clear enough to embark on engineering development. Considering that the latter will require additional studies and tests, it will take some 10 to 15 years to develop and build an experimental reactor or a demonstration unit which can be put into demonstration operation in about 20 years.