VISION FOR THE SECOND FIFTY YEARS OF NUCLEAR ENERGY

DEVELOPMENT STRATEGIES TOWARD A MAJOR ENERGY SOURCE

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ABSTRACT

This presentation summarizes the strategies' part of the INSC Report, "A Vision for the Second Fifty Years of Nuclear Energy," that looks at the global utilization of nuclear energy for the next 50 years from the perspective of the achievements in the first 50 years since the first nuclear chain reaction in 1942.

Based on the estimates of the world demand for nuclear energy in the next century, the availability of nuclear fuel resources was evaluated. Development of FBR and Pu-recycling is needed for the optimized utilization of U resources. From the review of status and prospect of FBR/Pu-recycling technology, strategies for the technology development are shown.

Utilization for non-electric purposes is another important area for nuclear energy to take part in the global energy supply of the future. Heat utilization and hydrogen production are discussed.

To ensure the long-term, global supply of nuclear energy for the sustainable development, other important tasks are also defined.

1. INTRODUCTION

Looking over the coming century, such global problems as population growth in developing countries, increase of energy consumption, and the resulting increases of carbon dioxide content in the atmosphere as well as other environmental problems make it important to secure energy sources with low environmental impact, high economic competitiveness, and long sustainable supply to satisfy worldwide energy demand.

Nuclear fission is the only demonstrated energy source to meet the above requirements. To ensure the long sustainable supply as the major energy source, it is necessary to adopt the FBR and Pu-recycling system.

Electric power is the major application of nuclear energy, though electricity comprises about 30% of the primary energy consumption at present. To make nuclear energy useful as the major energy source in the future, it is necessary to extend the nuclear energy application to non-electric purposes.

There are many tasks—technological, institutional, societal and international—for making nuclear energy as the major energy source. These tasks should be accomplished by many sectors of both producers and consumers of the energy.

These subjects are summarized and discussed based on the Report of International Nuclear Societies Council (INSC, 1996).

2. NEED FOR OPTIMIZED UTILIZATION OF U RESOURCES

Based on the estimates of the world demand for nuclear power by the World Energy Council (WEC, 1993), the availability of nuclear fuel resources for the global, long-term use of nuclear energy is evaluated. The relevant nuclear fuel resources are both the amount of natural uranium as a source of fissile uranium (uranium-235) and the amount of fissile plutonium. Two cases are investigated: without fuel recycling and with recycling (Aratani, 1994). The best use of available plutonium would be for recycling; i.e., as much plutonium as required would be recycled from all the spent fuel in the world.

The installed capacity of nuclear energy for the WEC reference case is shown in Table 1.

Table 1 Total Installed Nuclear Energy Capacity

Year	1990	2020	2050	2100
Total Capacity, GWe	321	570	2,519	6,745

The construction rate rises to an average of about 100 plants per year in the middle of the century when we add in the replacement of plants that are more than 40 years old. These plans are feasible, given the technology and industrial capacity available, even today.

The types of conventional nuclear reactor to be constructed are assumed to be PWR, BWR, and CANDU in the proportions in 1985. For the program with fuel recycling, the FBR is assumed to have a breeding ratio of 1.2 and a system doubling time of 40 years; i.e., the amount of plutonium available will double in 40 years. This is considered a feasible target.

Based on the Red Book (OECD/NEA & IAEA 1994), the world's "known" resources of uranium at a cost up to $130 per kilogram of uranium are 3.7 million tonnes, and "undiscovered" resources are 13 million tonnes; thus, the "total" or "speculative" resources are 17 million tonnes. If plutonium is not recycled, the cumulative demand for natural uranium will exceed the world' s current known resources around the year 2030. Uranium demand will exceed the world' s speculative resources around 2070, reaching 45 million tonnes in 2100 as shown in Figure 1.

When plutonium is recycled, the demand for uranium depends heavily on the date of introduction of the fast reactor. Two typical scenarios envisage the introduction of the FBR in 2030 and 2050, each with a transition period of 30 years. In this transition period, both conventional nuclear reactors and FBRs are constructed in parallel, but construction gradually shifts entirely to the fast breeder. The transition period is necessary to ensure adequate supplies of plutonium for the initial inventory and thus guarantee uninterrupted construction.

The cumulative uranium demand levels out at approximately 12 million tonnes when the FBR is introduced beginning in 2030 and at 23 million tonnes when the FBR is introduced in 2050. The 20-year delay in the introduction of the FBR makes a great difference in uranium demand. The supply of the expected amount of nuclear energy at reasonable cost and with reliability depends on the availability of resources that are recoverable with reasonable energy and cost. This in turn requires a suitable timing of the shift from conventional thermal reactors to FBRs.

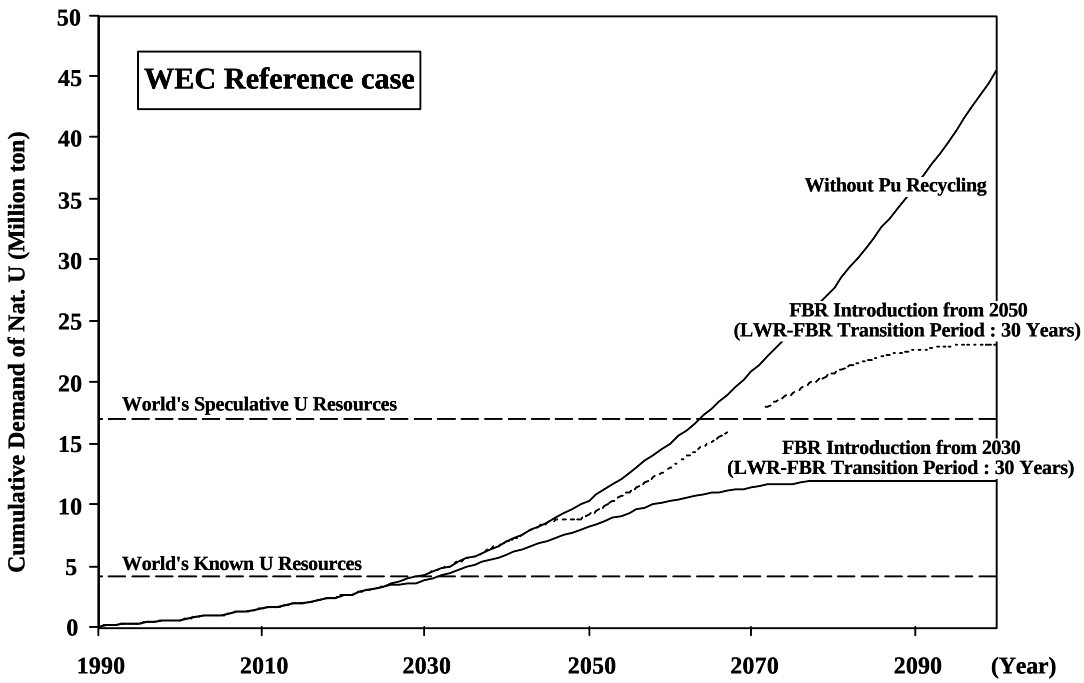

Figure 1 Cumulative Demand for Natural Uranium (Aratani, 1994)

Thus, if we try to supply the expected share of nuclear energy to satisfy the worldwide energy requirement by light water reactors, a shortage of uranium would be experienced around the middle of the next century. Commercial operation of fast breeder reactors by the middle of next century will become indispensable; so as a smooth transition of fissile materials from uranium 235 to plutonium can be achieved. If this plutonium recycling takes effect, about one million tons of depleted uranium that the world possess now could supply about one thousand years of nuclear power at the present world nuclear power generation level.

3. DEVELOPMENT OF FBR AND PU-RECYCLING TECHNOLOGY

3.1 Status and Prospect of Technology

Fast Breeder Reactors

The importance of recycling plutonium has been recognized since the beginning of nuclear energy development. Development of the FBR and the associated fuel cycle began in the United States and Soviet Union in the 1940s, in the United Kingdom in the 1950s, and in France and Japan in the 1960s. Now, India has an operating prototype reactor and China and South Korea are beginning FBR development. Metallic, nitride, and carbide fuels of mixed plutonium and uranium are being developed for FBRs as well as the more familiar mixed-oxide. A total of 21 fast reactors have been constructed so far.

All of the small fast reactors that have operated for a number of years proved to be safe, reliable, and easy to operate. The large fast reactors have been more difficult except one built in the former Soviet Union that is achieving consistently high load factors. Such a pattern of performance is not uncommon in developing new energy systems, and experience with the thermal reactors has shown that it takes a few decades to identify and correct all the operating problems with a particular design concept. The course of development will be no easier for the fast reactor.

The safety and reliability of FBRs have been explored in the prototype reactor stage. The economics will be determined in the demonstration reactor stage, which has been evaluated in the design studies of the European Fast Reactor (EFR) conducted jointly by France, the United Kingdom, and Germany, and of the Demonstration Fast Reactor (DFR) by Japan.

The EFR study projects that the construction cost of series-introduced plants will be 10 to 40% more than that of an LWR, depending on the country in which it is sited. The electricity generation cost (including fuel cycle cost) of the EFR is about 10% higher than that of an LWR in France (Asty, 1994). Construction cost estimates from the Japanese DFR study are 40% higher than that of the LWR for a first plant, falling to 10% higher for series-introduced plants of 1300 MWe (Miura, et.al., 1995).

If the results of research and development now under way in Europe and Japan, and previously in the United States, are applied to the FBR plant design, the construction cost might be cut to close to or less than that for LWRs. The operating cost (including fuel cycle cost) for FBRs is generally lower than that of LWRs when reliability is acceptable, based on European experience. Thus, the total generation cost of FBRs may become more favorable than that for LWRs, even if uranium price does not increase.

If construction of the next FBR demonstration plants, being designed in Europe and Japan, could start in the 2000s; the commercialization of FBRs by series construction could be demonstrated in the 2010s. Therefore, the global introduction of the FBR and its fuel cycle around 2030 could be technically feasible.

The removal of long-lived radioactive elements from wastes could reduce the environmental burden on repositories. Methods of destroying the long-lived elements in high-level radioactive waste by transmuting them in FBRs are being researched. Although the actual implementation of transmutation disposal methods may well be an extremely long term objective, the demonstration of its potential would reduce concerns about the long life span of radioactive waste.

Fuel Recycling

The fuel for the current fast reactors is mixed plutonium and uranium oxide (MOX). Mixed nitride and metallic fuels are being developed. The development of MOX fuel is further advanced than that of other fuel types and cycles, and the performance of oxide fuel has already been demonstrated.

A nitride fuel core gives better neutron economy than an oxide fuel core because the neutron energy spectrum is harder. Therefore, a nitride fuel FBR can respond more flexibly to requirements such as conversion/breeding ratio, actinide burning, long core life, or compact core. Furthermore, the Purex reprocessing process used for oxide fuel can be applied to nitride fuel. However, it may be necessary to use enriched nitrogen-15 in the nitride fuel in order to avoid, for environmental reasons, the formation of carbon-14 from nitrogen-14 during irradiation. In the future, if technologies such as granulated fuel, vibration packing, and sodium-bonded fuel pins and the dry reprocessing process can be applied commercially to nitride fuel, then the nitride fuel systems are likely to become superior in cost-competitiveness to oxide fuel systems. The nitride fuel systems are currently being investigated in France and Japan.

A metallic fuel core has neutronic characteristics similar to a nitride core. Its total fuel cycle has a number of advantages. In the United States, a pyroprocessing technique has been developed whereby spent metallic fuel is reprocessed at the reactor site. The plutonium is not separated from the higher, radioactive actinides; they are recycled together in the reactor and never leave the reactor site. The long-lived radioactive minor actinide elements that otherwise would be disposed of as waste are irradiated in the fast breeder core and transmuted into elements with shorter half-lives, thereby lightening the burden of radioactive waste disposal.

The dry reprocessing methods such as the pyroprocessing technique demonstrated experimentally in the United States, if commercialized, may offer an alternative to aqueous Purex reprocessing. The dry reprocessing methods can be applied not only to the FBR fuels—metallic, nitride, and oxide—but also to the oxide fuels of LWRs. Thus, dry reprocessing may bring new options to the overall fuel cycle.

The oxide fuel FBR and fuel cycle systems are in the prototype-to-demonstration stage of development. On the other hand, both metallic and nitride fuel FBRs and their fuel cycle systems are in the development-to-testing stage, therefore the commercial feasibility of these systems can only be evaluated after substantial progress has been made.

3.2 STRATEGIES FOR TECHNOLOGY DEVELOPMENT

Institutional Strategies

- It is up to the advanced nations to come up with exploiting energy with higher potential, because developing nations will naturally opt for readily available sources of energy. As nuclear energy, especially the fast breeder reactor system with plutonium recycling, has the highest potential for the global supply of energy, advanced nations should strive for the development of advanced nuclear power plants, especially the fast breeder reactor system with plutonium recycling.
- Governments of the advanced nations should support the developmental projects of the fast breeder reactor system, as the projects are for long term and the outcome is beneficial to the world.
- R & D organizations, design/engineering organizations and plant/fuel suppliers in advanced nations, individually or in groups, have the ability to undertake development works of the fast breeder reactor systems.
- The development works should be made efficiently through the effective utilization of technology among the organizations by such cooperative measures as exchanges of information and joint works.
- A cooperative action for the development of FBR/Pu-recycling technology among the R & D organizations in the advanced nations is envisaged to play an important role hereafter. In this cooperative action, major FBR/Pu-recycling development organizations and facilities will have their own roles and be expected to make contribution under the joint direction and management. Therefore, the FBR/Pu-recycling related staff/facility of these R & D organizations will become a part of 'International Laboratory' for FBR/Pu-recycling development.
- As the global demand for the fast breeder reactor system is expected to be large in the future and the market for the system is broad when the system is commercialized, enterprising or commercial development works might start in some stage, which should be welcomed.

Technological Strategies

- It is important to keep the development of reactors in coordinated step with the development of the fuel cycles, including both the front end and the back end of the fuel cycles.
- For the development of fast breeder system with plutonium recycling, all the accomplishments so far achieved over the world in research and development and in design, construction and operation of fast reactor plants and reprocessing plants should effectively be utilized.
- The target of fast breeder system development should be equal to or higher than the level of thermal neutron reactors, at the time of commercialization, with respect to safety, economy and reliability.
- Technology development and operation experience for large plants should further be made even for the mixed oxide fuel reactor with Purex reprocessing, of which type is the most realistic and reliable way to pursue early commercialization of fast breeder reactor system.

- Reactor and reprocessing plants in the next stage for technology demonstration and operation experience should have enough capacity to extrapolate to commercial size plants. The 1500 MWe EFR reactor plant and 60 - 80 ton/year MAR-600 and EDRP reprocessing plants, which have been designed in Europe, are suitable in capacity for this purpose.
- Technology of metallic and nitride fuels and dry reprocessing processes should be developed in a longer-term target.
- Transmutation of long-lived elements in high-level radioactive waste should be developed in a longer-term target.

4. NUCLEAR ENERGY FOR NON-ELECTRIC PURPOSES

About 30% of the world's primary energy is converted to electricity. The remaining 70% is consumed mainly as process and space heating and in transportation: ships, surface vehicles, and aircraft. The ratio of electric power to total energy consumption is increasing year by year and is estimated to rise to 50 to 60% in the future. As it is essential to reduce the use of fossil fuels from the viewpoints of both resources and the environment, it is important to explore the possibility of nuclear energy replacing other energy sources for non-electric applications.

4.1 Useful Heat from Nuclear Energy

Thermal energy generated in nuclear reactors can have a number of end uses:

- To produce electrical energy by steam turbine or gas turbine
- To produce chemical energy by fossil fuel reforming or hydrogen production
- To utilize the thermal energy itself by transportation of heat.

Possible non-electric applications of nuclear energy are classified by the temperature of reactors as follows:

- Low temperature (up to 300°C)

  Utilization of condenser cooling water in

  agriculture

  aquaculture

  Utilization of hot water and steam in

  regional air conditioning

  industrial process heat (e.g., the pulp and paper industries)

  desalination
- Intermediate temperature (300 to 600°C)

  Utilization of steam as industrial process heat (e.g., petroleum refining)
- High temperature (greater than 600°C)

  Utilization of high-temperature gas as industrial process heat (e.g., hydrocarbon reforming, coal liquefaction, hydrogen production).

It is expected that future large-scale applications of nuclear energy for non-electric purposes will include

- Regional heat supply or home heating in areas where conditions of weather and siting (e.g., high density of use) are suitable;
- Desalination and industrial process use of low- and intermediate-temperature heat, using dual-purpose plants supplying both electricity and heat or by single-purpose plants supplying heat, in areas where the demand and site are suitable;
- Production of hydrogen by high-temperature thermal reforming of natural gas; the direct application of nuclear heat to high-temperature chemical processes requires the development of suitable materials for high-temperature chemical reactions in the processing system connected to a nuclear reactor.

4.2 Hydrogen Production

As the percentage of electricity generated by nuclear energy increases, the load factor of nuclear power plants tends to decrease because of the need to follow the load. This increases the unit cost of electricity from these capital-intensive plants. Nuclear power plants are operated more economically at their rated power (base-load operation) because the fuel cost is a relatively small part - about 10% - of the total cost. Therefore, surplus power from nuclear power plants during off-peak periods can be made available relatively cheaply.

The pumped storage method is proven and currently used for providing low-cost peak power from high-capital-cost hydroelectric and nuclear power plants. Production of hydrogen by water electrolysis is another method of improving overall system economics by operating nuclear power plants to the maximum of their capacity. Of the various types of electrolysis, one using solid polymer membranes seems the most promising in terms of commercial viability and cost-effectiveness.

Hydrogen can be transported, stored, and efficiently converted to power. When burned, its sole combustion product is water; thus, the environmental effect is minimal. Hydrogen produced by nuclear energy will serve mainly as an energy carrier for the “hydrogen economy” in such applications as process and space heating and power source for transportation.

Hydrogen produced by nuclear energy will become commercially competitive when off-peak nuclear power is available or if the cost of nuclear power decreases significantly. As a step before the hydrogen economy is realized, the nuclear hydrogen could be used for the reforming of heavy oil, coal, or agricultural products.

5. REQUISITE FOR USING NUCLEAR ENERGY GLOBALLY

Factors that have limited the growth of nuclear energy will decrease if the industry is successful in demonstrating the advantages of nuclear energy, both in terms of economics and of environmental protection. These factors have been mainly;

- Public concern about nuclear energy accidents and achieving safe disposal of nuclear waste,
- The decreasing priority assigned to nuclear energy in many countries because of increasing competitiveness of other energy sources and falling oil prices,
- The failure of nuclear energy to take hold in developing countries because of lack of capital resources and local technological development.

These impediments will be overcome by establishing an international system of common safety principles, enhancing the public’s understanding of the safety of nuclear radiation, and providing multilateral support for regions promoting radioactive waste management. Energy specialists, by using their knowledge to provide information to the public on nuclear energy as an appropriate policy option and by presenting clear and unequivocal evidence on safety and economics, will contribute to reducing public apprehension.

To ensure a long-term supply of nuclear fuel, a smooth transition to the plutonium utilization era and the eventual commercialization of FBRs will be pursued as the policy in some regions. The most important requisites for attaining this goal will be the development of commercially viable technologies with sufficient economic advantage and the application of this technology in developing nations that will hold an important share of future increase in worldwide energy demand.

For the sustainable development of the world, it is important to promote the utilization of nuclear energy as a global, long-term major energy source. It is important that industry, academia, and governments, both sectors of producers and consumers of the energy, comprehend and support its necessity and importance, and take measures to achieve the common goal, both domestically and internationally. The important tasks are to;

- Ensure an understanding of the role of nuclear energy in the supply of energy,
- Attain societal and international consensus on nuclear energy utilization,
- Secure safety worldwide for the global use of nuclear energy,
- Define and implement policies for radioactive waste management,
- Determine the reserves of uranium and the timing of the need for plutonium recycling,
- Establish cost-competitiveness for FBRs,
- Improve fuel reprocessing technology,
- Further develop international systems to prevent nuclear weapons proliferation,
- Apply nuclear energy to broader needs, and
- Ensure a highly competent workforce to meet nuclear technology requirements.

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