CURRENT STATUS AND PROSPECTIVE OF NUCLEAR INDUSTRY INCLUDING ADVANCED NUCLEAR TECHNOLOGIES IN JAPAN

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1. Current Status and Prospective of Nuclear Energy

Fifty years passed since the US President Eisenhower's speech of "Atoms for Peace" in the United Nations in 1953. Japan had been prohibited to make nuclear research and development till then, however, after the President's speech, R&D on the peaceful use of nuclear energy could start as a national project. In 1956 Japan Atomic Energy Research Institute (JAERI) was established and a year after the first research reactor JRR-1 attained its first criticality. The first electricity generation by nuclear power was successfully made by the Japan Power Demonstration Reactor, JPDR in 1963.

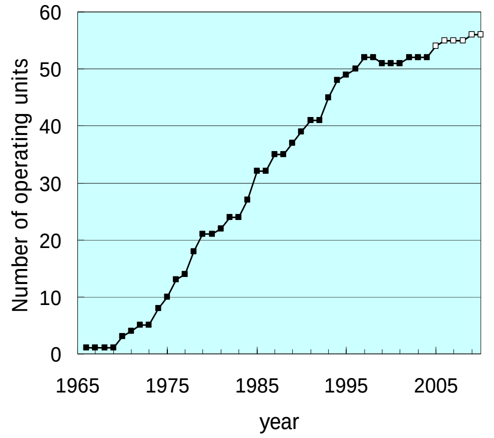
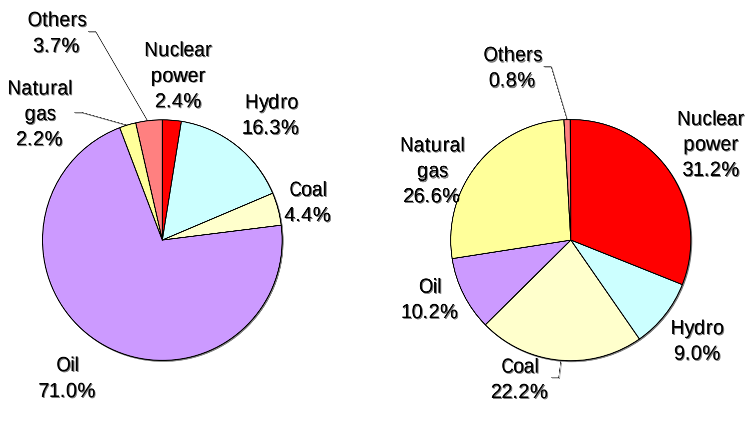


Figure 1 Change in the number of nuclear power plants in Japan

The first commercial power reactor was commenced its operation in 1966 (Tokai No.1: closed in 1998). It was the first oil crisis in 1973 that the tremendous efforts were initiated to make construction of new nuclear power plants in Japan in order to reduce the level of share of oil as energy source. The installation of nuclear power plants has progressed steadily for the last 20 years as shown in Fig. 1, and today, the total number of nuclear power plants operated in Japan is 52 with total installed capacity of 45,752 MWe. The nuclear power supplied 31.2 % of the total annual electricity generation, 950 TWh in 2002 although it supplied only 2.4 % of the total electricity generation in 1973 as shown in Fig. 2. On the other hand, the share by oil decreased from 71 % to 10.2 % in the



1973 2002

Figure 2 Electric power generation in Japan (source: METI etc.)

same time period. Nuclear power bears 13 % of nation’s primary energy source in the present, while the share of oil was reduced from 77 % to less than 50 % (see Fig. 3).

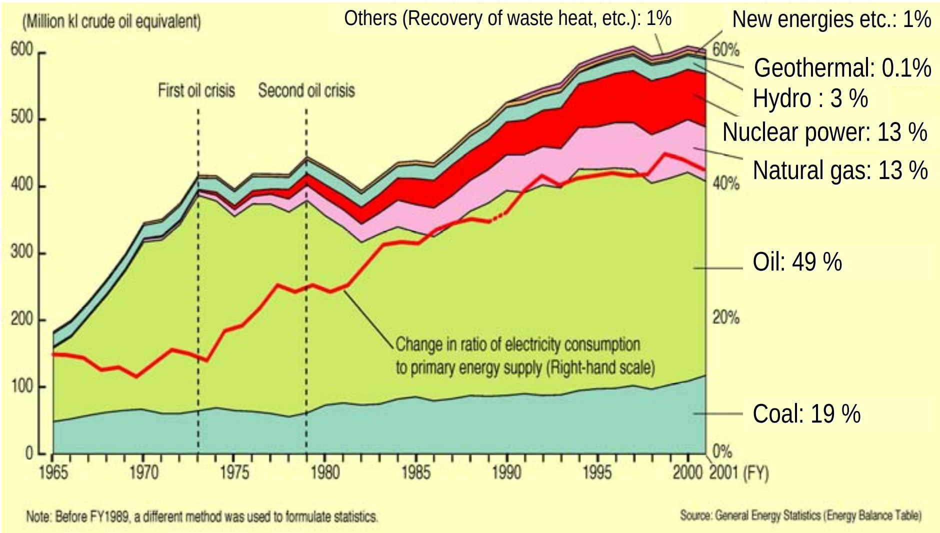


Figure 3 Change in the primary energy source in Japan (“Energy in Japan 2003” by METI)

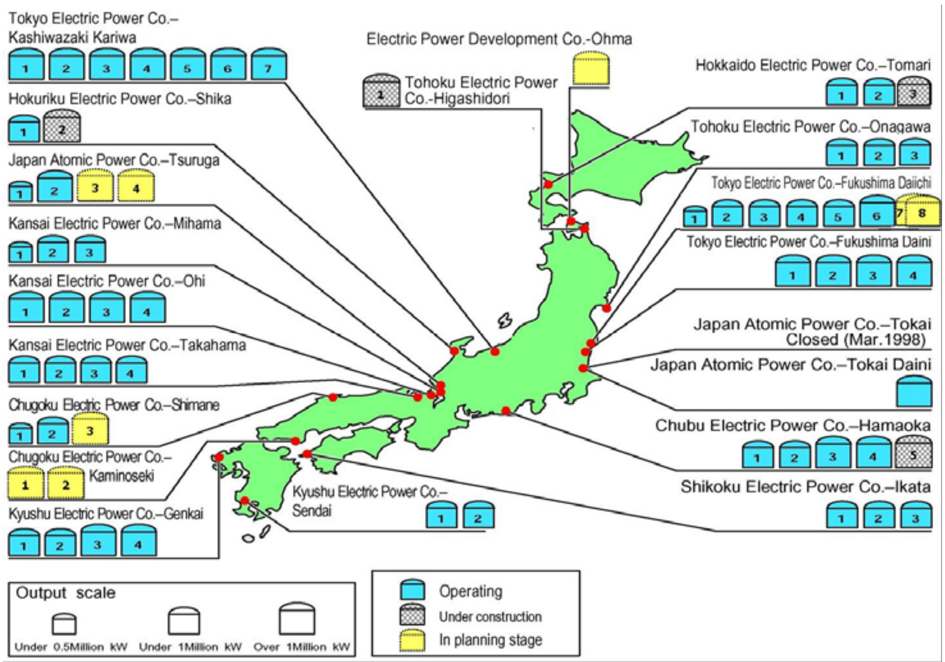


Figure 4 Nuclear power plants in Japan (as of 2004. 3)(Source: FEPC)

In a meanwhile, global warming by CO_2 emission from the use of fossil fuel became one of the most critical environmental problems facing world-widely. Kyoto Protocol was concluded in 1997 and Japan has made a commitment to reduce its total average greenhouse gas emissions by 6% against 1990 level between 2008 and 2012. In order to contribute for reduction of CO_2 emission, it is important to increase nuclear power generation, to save energy as much as possible, and to introduce renewable energies such as solar and wind. As for nuclear power generation in Japan, at least, another 4 plants are under construction currently, and several plants are in planning stage (see Fig. 4).

In recent several years, annually-averaged capacity factor of nuclear power plants was maintained at about 85 % in Japan (see Fig. 5). It is difficult to achieve more than 90 % of capacity factor, because periodical inspection by the government is required once per 13 months and each inspection spends 50 days or so. As can be seen in Fig. 5, the capacity factor of BWR fell off from the middle of 2002 to the last year. This is caused by the stop of the operation of all the nuclear power plants of Tokyo Electric Power Company (TEPCO) in August, 2002. Although cracks and/or indications in the core shrouds had been observed in several TEPCO's plants during the licensee's voluntary inspection since late 1980's, those had not been notified to the regulatory authority (Nuclear and Industrial Safety Agency (NISA)) and the repair records of those cracks had been deleted and concealed. In addition, data falsification by the company in the onsite inspections by the authority in 1991 and 1992 was revealed. As a result, not only the company but also nuclear business itself lost public trust and 17 TEPCO's nuclear power plants were obliged to be shut down for safety inspections. In order to prevent reoccurrence of falsification, related laws have been revised. Licensee's voluntary inspection was upgraded to licensee's periodical inspection. In addition, "Rules on Fitness-for-Service for NPPs" was reinforced in October 2003, where if defects are identified by a periodical inspection it is obliged is to evaluate its integrity in order to judge right or wrong of continuation of operations without any repair.

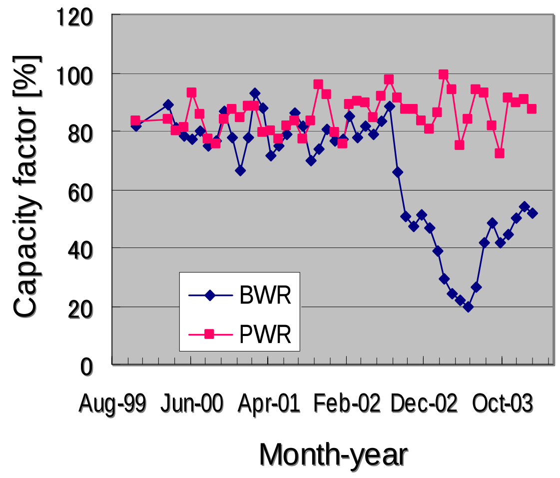


Figure 5 Change in capacity factor of nuclear power plants in Japan (source: Japan Atomic Industry Forum)

Now-a-days, electric utilities tend to build ABWRs with a capacity of 1,350 MW which are larger, and improved further comparing to BWRs. Furthermore, construction of an ABWR with full MOX core is planned. As for PWR, burnup of fuel is extended from 48,000 MWd/t to 55,000 MWd/t and there is also a plan to build 1,500 MW APWRs.

While liberalization of electricity market has been extended stepwise in Japan since March 2000, there is a keen problem that the self sufficiency of energy is only 4 % and it becomes 20 % at most even nuclear energy is included as illustrated in Fig. 6. Therefore, discussion has been carried out whether the nuclear power can generate electricity with an attractive price comparing to other energy sources or not. As the base of the discussion, cost estimation of nuclear power generation was conducted. It included the backend cost, which was consisted of the construction and O&M cost of interim storage facility of spent fuel away from reactor plants, reprocessing plant, MOX fuel fabrication plant, the disposal cost of TRU waste and high-level radioactive waste, the decommissioning cost of reprocessing facility etc.

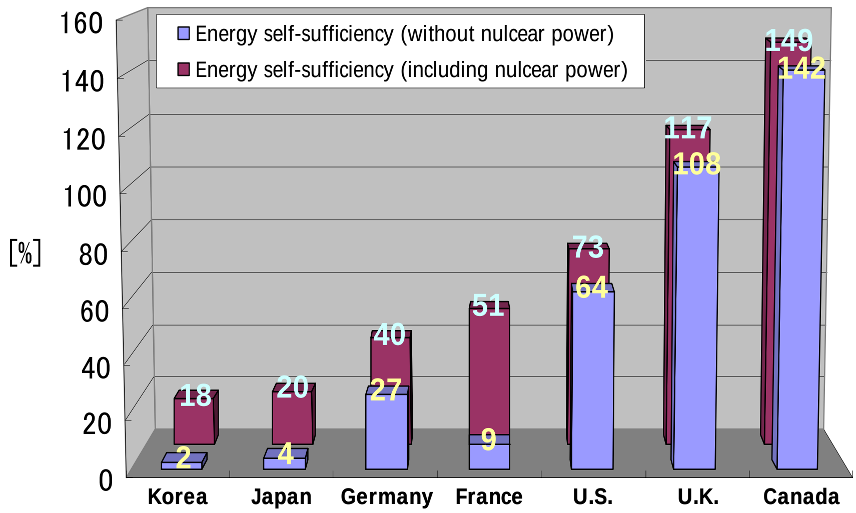


Figure 6 Self-sufficiency of energy among selected countries
(source: IEA/OECD, Energy Balances of OECD Countries 2001-2002)

As a result, the backend cost was estimated to be 0.81 yen/kWh and the total electricity generation cost of nuclear power was shown to be 5.3 yen/kWh. It was concluded that the resultant cost itself did not lose attractiveness comparing to other energy sources. However, discussion is being conducted further in order to find what and how nuclear power generation in Japan should be promoted to increase self-sufficiency and reduce CO_2 emission by private sector under the circumstance of growing electricity market liberalization, since the nuclear power generation requires extremely long period from the site selection to the disposal of radioactive waste, as well as huge initial investment.

2. Nuclear Fuel Cycle and Radioactive Waste Disposal

Pu utilization

Since Japan is a country with scarce natural resources, nuclear power generation is one of main energy sources, and furthermore, it is necessary to establish nuclear fuel cycle in order to utilize natural uranium resource more efficiently. Japan’s nuclear policy is to introduce plutonium recycle in Light Water Reactors (LWRs) as the first step, and to establish multiple plutonium recycle in Fast Breeder Reactors (FBRs) as the final step (see Fig. 7).

Pu utilization in LWRs is delayed due to the falsification of data on MOX fuel fabrication line in overseas company, although necessary research and development including test irradiation of MOX fuel subassemblies in the BWR and the PWR in Japan as well as safety review had been completed already. It is expected that Pu utilization will be started at several LWRs within a few years and finally 16 to 18 LWRs will be operated with MOX fuels.

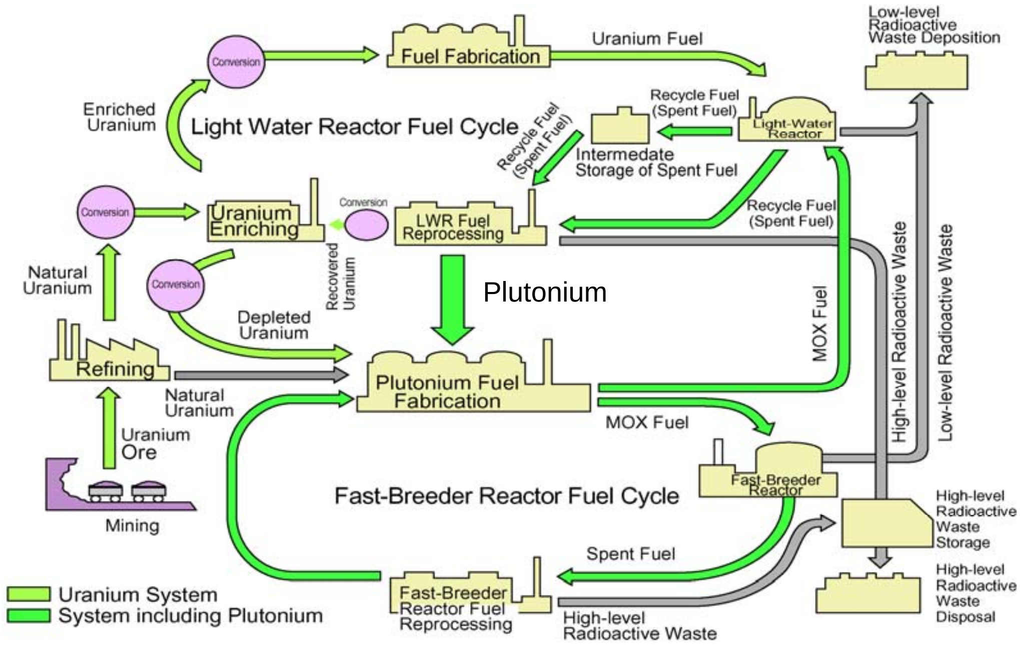


Figure 7 Nuclear fuel cycle including FBR cycle (Genshiryoku Zumenshuu, FEPC)

FBR development

Development of FBRs has been carried out from the beginning of 1960’s in Japan. A sodium cooled experimental fast reactor “JOYO” and a proto-type fast reactor “MONJU” were constructed. The JOYO has been successfully operated since 1977 and now is being operated at 140 MWt after two times of upgraded modification. The MONJU has not been operated for 8 years due to the sodium leakage accident. The modification of the plant hopefully will be started soon subject to the final agreement of the local government.

Furthermore, a feasibility study of FBR systems is being carried out, in which a wide range of technical options for coolant material, fuel type, reprocessing and fuel fabrication have been evaluated to explore relevant fast reactor system. In addition, Japan is actively participating in the Generation-IV International Forum (GIF).

Reprocessing

As shown in Fig. 8, the research and development of spent fuel reprocessing in Japan was conducted first in JAERI and 200 grams of Pu was successfully recovered in 1968. Then, a reprocessing plant with a capacity of 0.7 t/day was constructed at Tokai Works of Power Reactor and Nuclear Fuel Development Corporation (PNC) (former Japan Nuclear Cycle Development Institute (JNC)) in 1977. So far, about 1,000 t of spent fuels have been reprocessed.

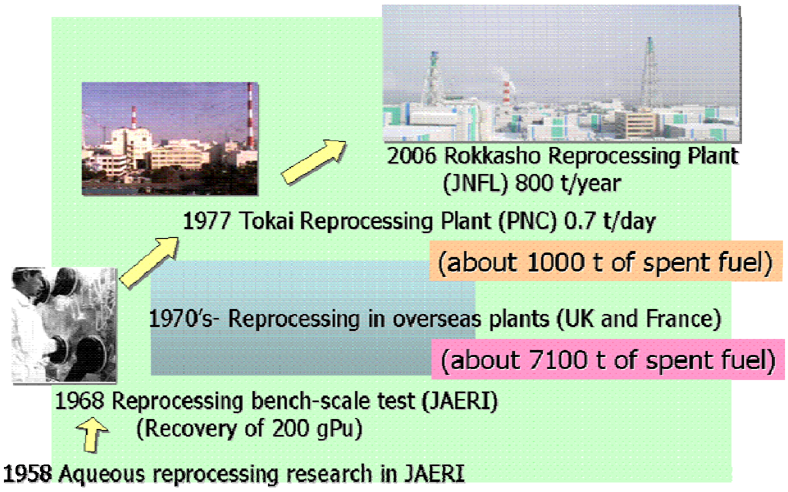


Figure 8 History of reprocessing activities in Japan (sources by JAERI, JNC and JNFL)

In parallel with the domestic reprocessing, electric utilities contracted with the reprocessors of France and UK to reprocess a total of 7,100 t of spent fuels. The construction of the domestic commercial reprocessing plant with a capacity of 800 t/y was completed and the reprocessing of real spent fuels will start in 2006.

In addition, research institutes like JAERI, JNC and Central Research Institute of Electric Power Industry (CRIEPI) are conducting development of advanced reprocessing technologies, such as simplified aqueous reprocessing, dry reprocessing and other techniques which are expected to be more economical with less environmental impact and have higher proliferation resistance.

Radioactive waste disposal

As concerns the management of radioactive waste from nuclear facilities, discussions were extensively carried out in the AEC from 1995 to 2000 and the waste was categorized into high-level radioactive waste and low-level radioactive waste as listed in Table 1. The low-level radioactive waste is divided into waste from power plants, waste containing TRU elements, uranium waste and waste from RI facilities & institutes. The disposal concept for each type of radioactive waste was established and safety regulation, safety guidelines and legislation for each disposal concept are being discussed and will be prepared by Nuclear Safety Commission (NSC) of Japan and NISA. In addition, management of waste with extremely low-level radioactivity, which would not be necessarily treated as radioactive waste, is being discussed and the NSC will determine a threshold level to categorize as non-radioactive waste, *i.e.* clearance level.

Among them, legislation of the disposal of high-level radioactive waste was made in 2000, which required to establish an organization to implement disposal business and an organization to manage the fund for disposal collected from the electric utilities. The implementing body (Nuclear Waste Management Organization of Japan, NUMO) was established and recently launched a campaign to search candidate sites for preliminary investigation of the nature of soil and the ground. Also, research and development related to the disposal is carried out in a wide range in this field.

Table 1 Categorization of radioactive waste in Japan

Waste		Plants
High-level radioactive waste		Reprocessing plant
Low-level radioactive waste	Waste from power plants	Nuclear power plant (O&M and decommissioning)
	Waste containing TRU elements	Reprocessing plant and MOX fabrication plant
	Uranium waste	Enrichment plant and fuel fabrication plant
	Waste from RI facilities, institutes etc.	Research laboratories, hospitals and industries

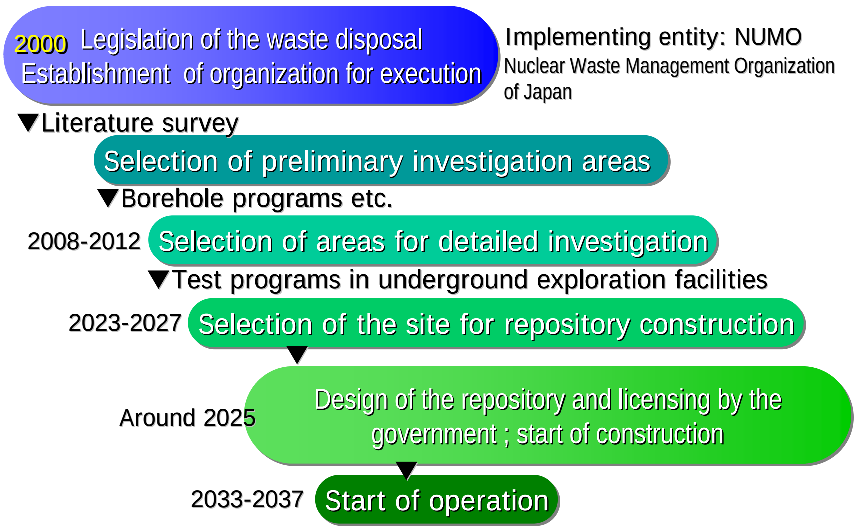


Figure 9 Projected schedule of high-level radioactive waste disposal in Japan

As a future alternative for the treatment of high-level radioactive liquid waste arisen from reprocessing to reduce radiotoxicity by a factor of at least one hundred, research and development of partitioning and transmutation technology has been carried out by JAERI, JNC and CRIEPI. Accelerator driven system (ADS) and FBR system are studied as candidates for the treatment. ADS system has been received increased attention due to its potential to accommodate light water reactor fuel cycle systems and to have safer characteristics. JAERI is constructing a highly intense proton accelerator (J-PARC) partly to investigate transmutation of minor actinides.

3. Advanced Nuclear Technologies

Advanced radiation application

Radiation has been used in a wide variety of fields such as industry, agriculture and medical treatment. Many new materials with special function by radiation grafting, radiation cross-linking of polymers by utilizing electron beam and gamma-ray have been created, particularly in JAERI. New absorbents to collect uranium from seawater and a new-electrolyte membranes for fuel cell, for example, were developed. As concerns recovery of uranium from seawater, one kg of uranium was successfully recovered from seawater in which three mgs of uranium are dissolved per one ton. Other examples are new mutants induced by ion-beam irradiation: new carnation flowers with various colors and shapes have been created by 220 MeV carbon.

On the other hand, various kinds of radiation can be used as probe in advanced science and technology. Neutrons can be used in variety of studies in the fields of materials science, life science and engineering technology. One of the studies is structure analysis of protein, especially of hydrogen and hydrated water in the protein, which are very important to understand the function of the protein. Other R&D activities using neutron are, structure analysis of magnetic domain in Co-Cr film and non-destructive residual stress analysis of industrial products and parts. Neutrons produced in the research reactors have been used, however, in order to respond the requirement of a great number of neutron users and to promote neutron transmutation, nuclear and particle physics, JAERI and High Energy Research Organization (KEK) are constructing the J-PARC in the Tokai establishment of JAERI.

Synchrotron radiation is an excellent probe to analyze structure and dynamic behavior of materials. In general, fine precious metal particles dispersed in a solid support are used as catalyst to remove harmful component in automobile engine exhaust gas. Recently, Japanese Daihatsu Motor company developed Pd-perovskite catalyst in which deterioration of the catalytic activity does not occur. The mechanism was revealed using synchrotron radiation at Super Photon ring 8 GeV (SPring-8) by JAERI’s scientists.

High temperature gas-cooled reactor and hydrogen production

The establishment of high temperature gas-cooled reactor technologies and application of nuclear heat to hydrogen production in the real nuclear plant are very important to open new nuclear era. In Japan, a test reactor HTTR was constructed at JAERI and is being operated since its first criticality in 1998. Outlet coolant temperature of 850 ^{o}C, which is the highest temperature of reactor outlet in the world, was demonstrated so far, which would enable to have a wide range of application as heat source. The outlet temperature of 950 ^{o}C will be also attained very soon as the highest one in the HTTR. As a promising carbon-free method for hydrogen production using the nuclear heat, high-temperature thermochemical decomposition of water is being focused. The Iodine and Sulfur (IS) process is selected and has been developed. In 2003, continuous and stoichiometrical production of hydrogen was demonstrated with the production rate of 30 liters/h for 20 hours. The pilot scale test of $1m^3/h$ is now in preparation.

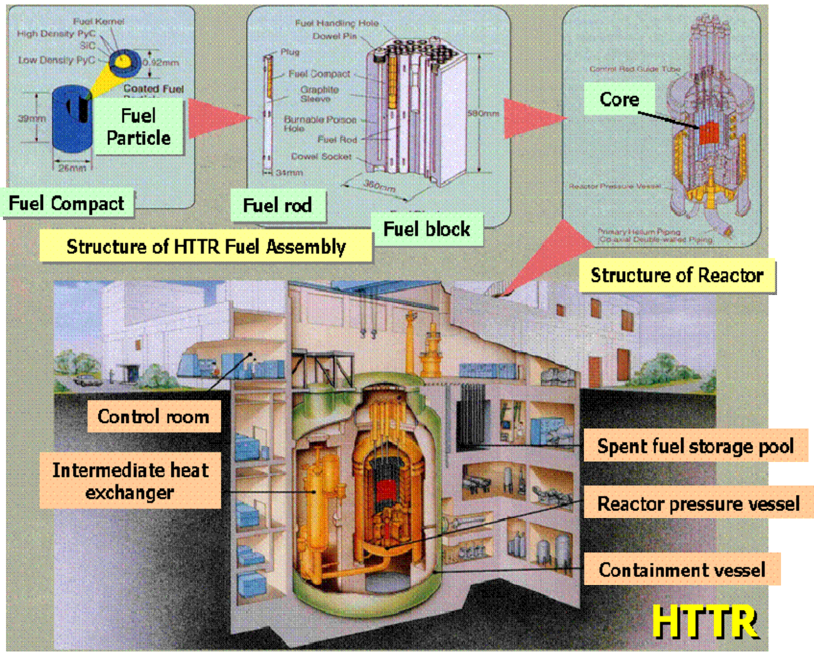


Figure 10 Outline of HTTR (by JAERI)

Fusion research and ITER project

Japan has been also devoted to make research and development of fusion for long time. Various fusion systems, such as Tokamak, Helical, RFP, Mirror and Laser, have been studied in the universities and national research institutes.

JAERI Tokamak-60 (JT-60) started its operation in 1985, and achieved the break-even condition in the autumn of 1996, and has continued to produce remarkable scientific results including the world records of fusion gain (=1.25), fusion product ($=1.77 \times 10^{28}$ $m^{-3}s^{o}C$) and Ion temperature (=520 million^{o}C) as shown in Fig.11. Consequently, JT-60 has greatly contributed to the design activity of the International Thermonuclear Experimental Reactor (ITER), which is shown in Figure 12.

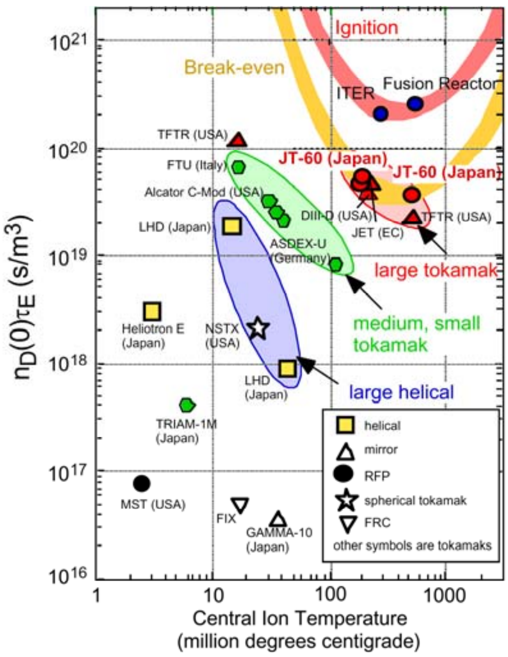
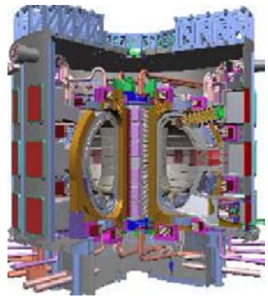


Figure 11 Progress of Fusion Plasmas (by JAERI)

ITER Project is an international collaboration to attain burning plasma of deuterium-tritium (DT) and demonstrate the scientific and technological feasibility of fusion power. Conceptual Design Activities (CDA) began in 1988 by collaboration of the European Union, Japan, the Russian Federation and the United States of America. After the CDA between 1988-1990, Engineering Design Activities (EDA) were executed between 1992-1998. In July 1998 the ITER Parties were unable, for financial reasons to proceed to construction of the design proposed at that time. It was therefore decided to investigate options for reduction of the cost. The extended EDA were carried out by ITER Parties except US which withdrew from the ITER Project then, and the modified design was completed in July 2001. Consequently, the cost of ITER for construction was reduced from ¥1000B to ¥500B. In the EDA, extensive R&D was carried out to prove the viability of new technologies, and the seven large R&D projects such as Central Solenoid Model Coil and Vacuum Vessel Sector, were established to demonstrate fabrication feasibility of major components of ITER. Since the start of the CDA, almost ¥160B has been spent and the costs were shared in the ITER Parties as roughly one-third to EU, Japan and US plus Russia each. Through those activities ITER is now ready for a decision on construction. The US rejoined to the Project in 2003, and also China and Korea newly participated in the ITER Parties.



Fusion power : 500 MW
Plasma major radius : 6.2 m
Plasma minor radius : 2.0 m

Figure 12　ITER

4. Conclusions

(1) Nuclear power is the key electricity source which bears one third of the total electricity production in Japan, and increases self-sufficiency with reduction of CO_2 emission. Promotion of Pu utilization in LWRs is necessary together with FBR fuel cycle. However, the growing electricity market liberalization induces a problem how nuclear power generation in Japan should be promoted by private sector.

(2) The extensive research and development for radiation applications have been performed and lots of significant products have been attained in the fields of industry, agriculture and medical treatment. On the other hand, various kinds of radiation such as neutron, electron, photon, positron, etc. have contributed to the progress of advanced science and technology as excellent probes.

(3) Japan has pioneered in the development of HTGR in the world and is making further effort to apply nuclear energy to non-electricity production field such as hydrogen production. The high-temperature thermochemical decomposition of water with the IS Process is progressing in Japan.

(4) Japan has attained the world's foremost level of R&D in nuclear fusion and been deeply involved in the ITER Project from the beginning of the project. Japan hopes that the construction of the ITER will be able to start smoothly very soon and it will produce valuable fruits.