ROLE OF FUSION ENERGY FOR THE 21 CENTURY ENERGY MARKET AND DEVELOPMENT STRATEGY WITH INTERNATIONAL THERMONUCLEAR EXPERIMENTAL REACTOR

Rôle de l'énergie de fusion dans la production énergétique du 21^{e} siècle et stratégie de développement avec le réacteur thermonucléaire international ITER

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1. Introduction (Introduction)

It is a common understanding that increasing CO_2 emission would lead to global warming which has a significant impact on the human life. World energy suppliers are making an important challenge in reducing annual CO_2 emission rate such as by changing COAL-fired plant to LNG-fired plant. Nuclear fission power can also contribute to significant reduction in CO_2 emission to the atmosphere. But, the public acceptance should be improved to contribute to this issue.

Fusion is an energy source of the Sun and the Star. It is a quite challenging scientific project to realise controlled fusion power generation on the Earth. Fusion is safer and environmentally attractive energy source with significantly lower radiological toxic hazard potential than that of fission plant and fairly lower CO_2 emission rate than that of fossil power plant.

The world fusion research has been focused on confinement of high temperature plasma for 40 years. And now, we have produced high temperature plasmas up to 520 Million Kelvin in fusion experimental device JT-60U at Japan Atomic Energy Research Institute far enough to fuse deuterium and tritium to produce fusion energy. It is a time to proceed to the next step, namely to build ITER as an International Thermonuclear Experimental Reactor to demonstrate feasibility of fusion energy for the 21 century.

In Japan, Fusion Council under Atomic Energy Commission formed the Subcommittee for Fusion Development Strategy (Chair : Prof. N. Inoue) to investigate technical feasibility of fusion energy including advantages and conditions of Fusion Energy as an energy option and to identify its development strategy towards the future electricity production with DEMO [1].

We will report key observations and conclusions in the subcommittee such as advances in fusion research, advantages of Fusion Energy in comparison with fossil, fission and renewable, preliminary assessment of target conditions to come into the energy market, and the development strategy with ITER. Here, ITER is an international co-operation program among the EU, the Russian Federation and Japan (and the US initially) to demonstrate controlled fusion reaction at power level of 0.5GW [2].

2. Progresses in Fusion Research (Progrès dans la recherche sur la fusion)

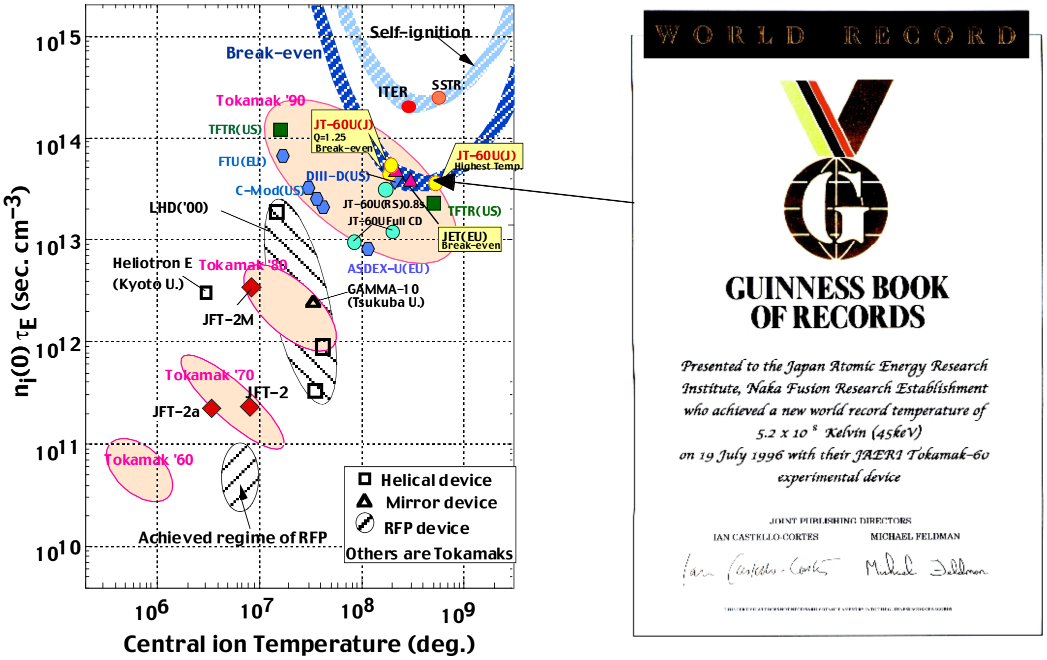
Fusion reaction is an energy source of the Sun whose diameter is 1.4 million km. Dense (150g/cm3) and high temperature (15million Kelvin) plasma is confined at the centre of the Sun by its gravitational force and Proton-Proton fusion reaction takes place there. Part of the fusion power in the Sun is converted to the sunlight and travelled to the Earth. All lives on this Planet receive the blessing of sunlight.

Fusion research is addressing realisation of the Sun on the Earth in a sense that fusion reaction as an energy source of the Sun is realised on the Earth. Electromagnetic force (or magnetic pressure $B^2/2\mu_0$) is utilised to confine high temperature plasma (~200 million Kelvin) within the diameter of ~16m to realise controlled D-T (deuterium and tritium) fusion reaction on the Earth.

It is memorial that exactly half a century have passed since an official announcement by the past President of Argentina, Mr. Peron, in 1951 on controlled fusion experiments which attracted a strong positive public interest on fusion.

Progresses in Fusion Research is shown in so-called Lawson diagram ($n\tau_E$,T), where n, τ_E and T are plasma density(m^{-3}), energy replacement (confinement) time (s), and the plasma temperature (Kelvin), respectively. Needs for higher n, τ_E ,and T come from higher reaction rate (~n^2), low power demand to sustain high temperature (~$1/\tau_E$), and high enough temperature to fuse D and T, respectively. Figure 1 shows the Lawson diagram for conditions of Break-even and Self-ignition. Here, Break-even and Self-ignition conditions are defined as Q (=fusion power/ external heating power) =1, and infinity, respectively.

Fusion research made significant progresses since the tokamak confinement concept was initiated and developed in former Soviet Union in 1960s. An order of magnitude increases in both temperature and $n\tau_E$ was achieved in a decade. Now we have reached a stage of Break-even condition in JET (EU) and JT-60U (Japan) in 1992 and 1996, respectively. And the maximum plasma temperature achieved in JT-60U is 520 million Kelvin and is a world record as certified by Guinness Book of Record as shown in Fig.1.



GUINNESS BOOK
OF RECORDS

Presented to the Japan Atomic Energy Research
Institute, Naka Fusion Research Establishment
who achieved a new world record temperature of
5.2 x 10^{8} Kelvin (45keV)
on 19 July 1996 with their JAERI Tokamak-60
experimental device

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Fig. 1 Lawson diagram showing Break-even (Q=1) and Self-ignition (Q = infinity) conditions as target for fusion research. Progresses in a few decades (1960's to 1990's) are shown in the figure. Right hand figure shows a certificate by Guinness Book of Records for the achievement of world record temperature in JT-60U. (Diagramme de Lawson montrant les conditions nécessaires pour obtenir un bilan d'énergie positif pour le plasma (Q=1) et l'ignition ($Q \rightarrow \infty$). Les progrès réalisés en quelques dizaines d'années (1960 à 1990) sont illustrés sur la figure. A droite, se trouve le certificat du Livre des Records Guinness pour l'obtention du record mondial de température dans JT-60U.)

Progress speed of the fusion research can be shown by the yearly variation of achieved value of Fusion Triple Product, $n\tau_E T$. Fig.2 compares the increasing speed of fusion triple product with that of the memory size of DRAM which is one of the typical high technologies whose progress speed is extremely high, achieving 10 times larger size in every 5 years.

World fusion community has made a significant job to increase fusion triple product $n\tau_E T$ from 10^{15}keV s m^{-3} in 1960's to 10^{21}keV s m^{-3} in 1990's. This speed is exactly the same speed as that of DRAM. Only several times increase from the present level is required for sustained controlled fusion power production.

In these research and development, competition between various machines in various countries worked well to accelerate the progress speed. This world competition is now soft-landing to the achievement of fusion triple product needed for the fusion power station through world co-operation in ITER project.

Although there are a lot of research subjects to be done to realise actual fusion power station as discussed in detail in the subcommittee's report [1], we are sure that world fusion research is ready to come into a new phase of demonstration of significant fusion power generation in ITER.

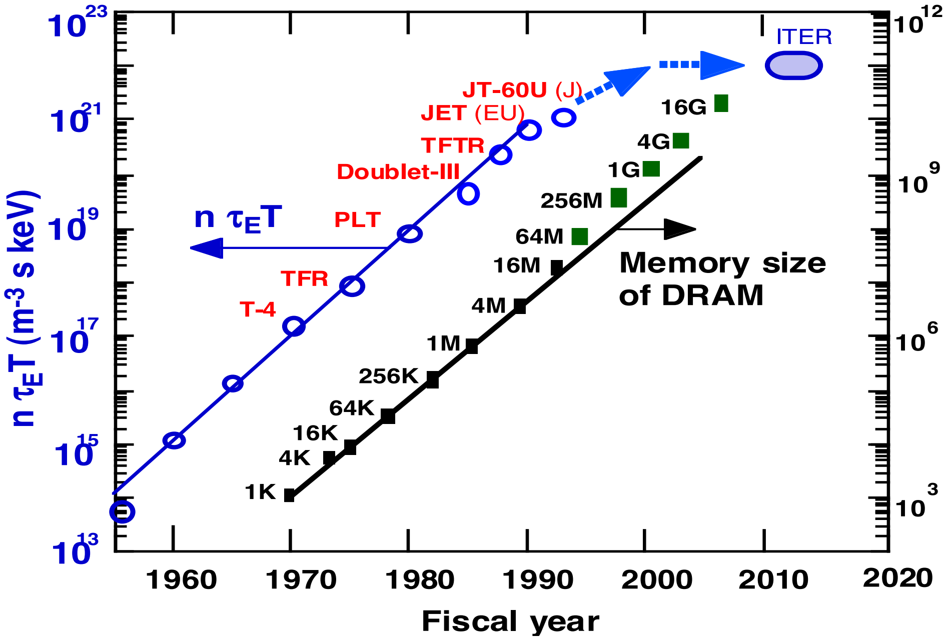


Fig. 2 Comparison of progress speed of fusion research and development with that of DRAM as a typical high technology in the 20th century. Both fusion and DRAM have same progress speed of 10 times increase in 5 years. World record of fusion triple product is 1.5×10^{21} keV s m^{-3} achieved in JT-60U. (Comparaison de la vitesse de progression des recherches sur la fusion et des recherches sur les DRAM qui sont considérés ici comme une technologie de pointe typique du 20e siècle. La fusion et les DRAM ont la même vitesse de progression correspondant à une multiplication par un facteur 10 en 5 ans. Le record mondial du produit triple est de $1{,}5\times10^{21}$ keV·s·m^{-3} et a été atteint dans JT-60U.)

3. Fusion as a Promising Energy Source in New Millennium
(La fusion: une énergie pleine de promesses pour le nouveau millénaire)

3.1 Long Term Perspective of Energy Supply and Role of Fusion
(Prévisions à long terme pour la production d'énergie et le rôle de la fusion)

18th World Energy Congress is an epoch-making conference as a first World Energy Congress in new millennium. It is therefore timely to talk about the long term perspective of energy supply for a few millennium time scale as shown in Fig.3.

The energy consumption is closely related to the human population and 20th century is quite unique century when the world population grows very rapidly associated with the mass food production with mechanised farming. The population should be stabilised in the new century at certain level, for example, 12 billion peoples.

If average annual energy consumption per person is 1.67 toe (tonnes oil equivalent), energy supply of 20 G toe/year should be done to keep comfortable living style. The fossil energy resource is a precious gift to the human being from the fusion reaction in the Sun which are condensed under the Earth during a few hundred millions of year. This precious gift will be expired within a few centuries if most of the energy supply comes from fossil fuel. We will probably call this period as Short Fossil Era late in this millennium. After this Era, we need large-scale, non-fossil energy sources such as renewable, fission and fusion.

It would be difficult to reduce our annual energy consumption significantly, for example, by an order of magnitude for the longer utilisation of fossil fuel.

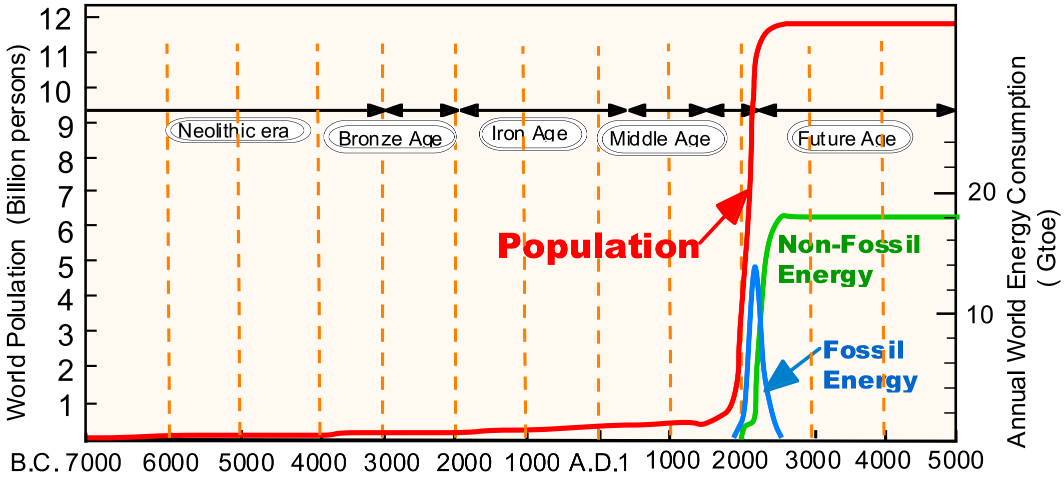
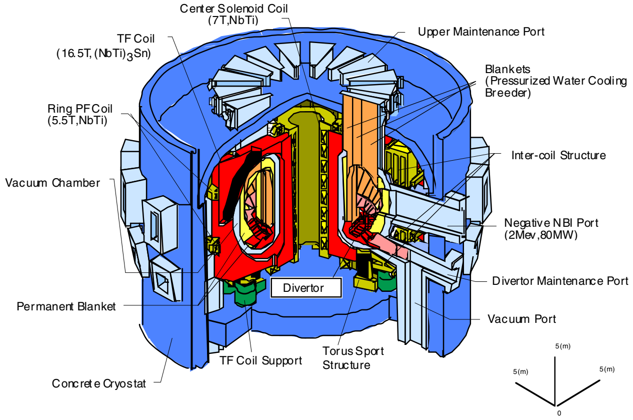


Fig. 3 Long-term trend of world population and energy consumption. World population grew very rapidly in 20th century associated with massive food production with mechanised farming. The energy consumption also grew very rapidly in later half of 20th century and will continue to increase in 21st century. Even if we assume world population saturates at 12 billion, we must provide 20 Gtoe/year even if the average annual energy consumption per person is limited to 1.67 toe. (Evolution à long terme de la population mondiale et de la consommation d'énergie. La population mondiale a crû rapidement pendant le 20e siècle avec la production massive de nourriture due à la mécanisation des exploitations agricoles. La consommation d'énergie a également crû rapidement pendant la 2e moitié du 20e siècle et va continuer à croître pendant le 21e siècle. Même si on fait l'hypothèse d'une saturation de la population mondiale à 12 milliard d'habitants, il faut prévoir une production d'énergie de 20 Gtoe/an avec une consommation annuelle par personne limitée à 1,67 toe (toe : énergie d'une tonne de pétrole).)

3.2 Assessment of Fusion Energy Resources
(Evaluation des réserves énergétiques pour la fusion)

Capability of fusion energy production is assessed for both fuel resources and material resources for the reactor. Fusion reactor design SSTR (Steady State Tokamak Reactor) [3] is used as a reference fusion power plant. The SSTR is designed to have a fusion power output of 3 GW and generate an electrical output of 1.08 GW as shown in Fig.4.



Bird's-eye view of SSTR

		Design Value
Plasma Current	I_p	12MA
Toroidal Field Coil	B_t	9T
Major Radius	R	7m
Aspect Ratio	A	4.1
Elongation	κ_{95}	1.85
Normalized Beta	β_N	3.5
Fusion Output	P_F	3GW
Current Drive Power	P_{CD}	60MW
Net Electric Output Power	P_E	1.08GW
Fusion Gain	Q	50
Averaged Neutron Wall Load	$P_{neut.}$	3MW/m^2

Fig. 4 Bird's eye view of Steady-state Tokamak Reactor (SSTR) and its main parameters. (Représentation du Tokamak à fonctionnement continu (SSTR) et tableau de ses paramètres principaux.)

Fusion will be used primarily as a source of electricity. Operation of 1500 (1.1GWe level) fusion power stations corresponds to be electricity production of 1.25×10^7GWh/year (~1993 world electricity generation). Assuming plant life is 30years, necessary fuel and material resources can be estimated.

Deuterium (fuel) is almost limitless since its concentration in the fresh water is 144ppm. Lithium (mother material for tritium) is abundant in the seawater (233Gt). And the efficient extraction of Lithium from seawater is technically ready [4]. Reserve base of Beryllium (neutron multiplier) is very small 0.8Mt but the gross mineral resource estimated from abundance in the Earth Crust (=abundance x $10^{13.6}$) is 100Mt. Gross mineral resource of Niobium (raw material for superconductor) is 700Mt. The resource lives for Lithium (without recycling), Beryllium (with recycling) and Niobium (without recycling) are 1.5Myears, 70,000 years, 70,000 years, respectively. Fusion has enough fuel and material resources even for annual production of 20Gtoe primary energy for more than several millennium time-scale.

3.3 Fusion's Merit to reduce CO_2 Emission and Global Warming

(Avantages de la fusion pour la réduction des émissions de CO_2 et des effets liés au réchauffement planétaire)

The primeval atmosphere of the Earth in 4.6 billion years ago is believed to contain 100 atm of CO_2 similar to the present atmosphere of the Venus where the temperature is close to 500 Celsius by the greenhouse effect of CO_2. Most of the carbon in the atmosphere has been concentrated to the sea water, limestone and fossil fuel, etc. until 200 million years ago. This deposition of CO_2 into various materials results in a significant reduction of CO_2 pressure in the atmosphere to 0.03-0.04 atm.

Human being is now reversing this process through the massive combustion of fossil fuels in the Short Fossil Era. Total carbon weight in the present atmosphere is ~750Gt while 6Gt of carbon is released every year in a form of CO_2 into the atmosphere. This causes the rapid increase of CO_2 concentration in atmosphere as measured in Mt Mauna Loa in Hawaii. The increasing concentration of CO_2 would cause significant undesirable changes to our climate. This global environmental problem has been brought to the attention of the public, far before the appearance of exhaustion of fossil fuels. Countermeasures for this environmental problem have been enacted globally and are known as a framework treaty of climate change, which was established under the United Nations.

Energy sources with lower CO_2 emission rate per unit energy production are indispensable to prevent global warming. Global warming effect by electricity generation is measured on the basis of CO_2 emission unit defined below,

CO_2 emission unit = CO_2 emission during the life of the plant (construction, operation, fuel, methane leaks) / output to the power grid during the life of the plant.

Fig. 5 compares CO_2 emission units for fossil fuel power, fission power, fusion power, etc. CO_2 emission units for fossil power plants are divided into fuel-oriented emission and others. Although values of CO_2 emission units for coal and LNG fired plants are reduced with CO_2 sequestration, they are still larger than those of other energy sources. The value for the fusion is estimated one for various conceptual designs of fusion reactor. Fusion is one of three large-scale energy sources having lower CO2 emission unit (water, fission and fusion). CO_2 emission unit of fusion is larger than that of fission since there are many manufacturing processes during construction.

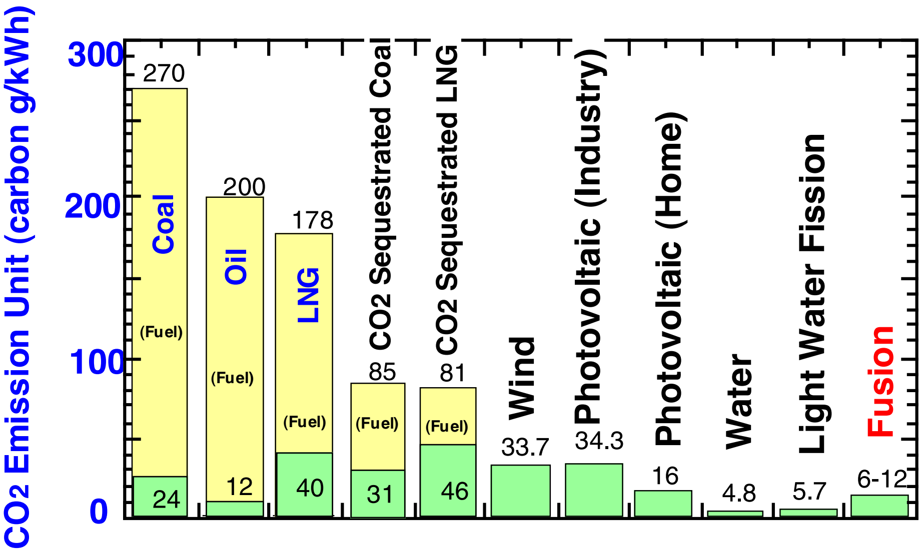


Fig. 5 CO_2 emission units for coal, oil, LNG (liquefied Natural Gas) fired powers, CO_2 sequestrated coal, LNG fired powers, wind power, photo voltaic power, water power, fission power and fusion power generation. Values are from [5] and [6]. (Emissions comparées de CO_2 pour les sources d'énergie suivantes : charbon, pétrole, gaz naturel liquéfié, charbon avec emprisonnement du CO_2, gaz naturel liquéfié avec emprisonnement du CO_2, vent (éolienne), cellules photovoltaïques, eau (hydraulique), fission, fusion. Les valeurs citées proviennent de [5] et [6].)

3.4 Fusion's Merit to reduce Potential Radiation Risk to Human Body

(Avantages de la fusion pour réduire le risque radiologique potentiel aux personnes)

Replacement of fossil power generation with environmentally friendly energy sources will be a primary issue in the 21st century. Nuclear power generations by light water reactor or fusion have low CO_2 emission units and can contribute to a significant reduction of CO_2 emission through the changeover from fossil to nuclear power generations.

However, nuclear power generation is associated with the potential risk of radiation exposure. This potential risk is quantified by the radiological toxic hazard potential (RTHP) or biological hazard potential (BHP). This is the value of the amount of radioactive nuclides (Bq) remaining in the reactor divided by the concentration limit in the air (Bq/m^3).

Tritium is a radioactive material from a fusion reactor and is a nuclide that can be handled with comparative ease. It emits beta rays with energies of 18.6 keV maximum and 5.7 keV average, and these rays can be shielded by one sheet of paper. Therefore, there is little danger from external exposure. If the tritium internally enters the human body, it does not remain in specific internal organs selectively. It is discharged from the body due to the metabolism at a rate with a 10-day half-life if it is in the form of water and at a rate with a 40-day half-life if it becomes an organic substance. Therefore tritium concentration limit in the air in the form of HTO is 5×10^3 Bq/m^3.

On the other hand, some radioactive materials produced in the light-water reactor are strontium-90, cesium-137, iodine-131, and so on. Iodine-131 is of most concern since it has the large influence on a human body. This nuclide is accumulated into thyroid gland and remains in the body for a long time. Therefore, it has a larger influence on the human body for other nuclides having the same radioactivity. So, Iodine-131 concentration limit in the air is 10 Bq/m^3, 1/500 times that for tritium.

Figure 6 shows comparison of RTHP of tritium and iodine-131 contained in 1GWe level fusion and fission power stations, respectively. It can be said that DT fusion is intrinsically safer than fission measured by their radiological toxic hazard potentials.

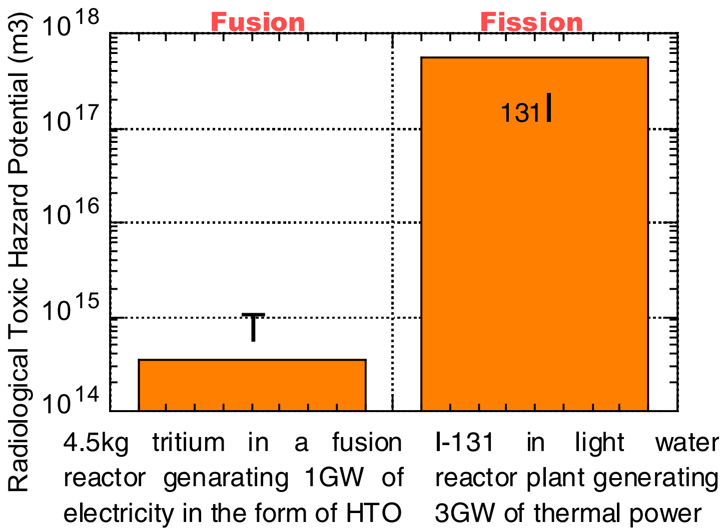


Fig. 6 Comparison of radiological toxic hazard potential (RTHP) between tritium and iodine-131 which are the typical volatile radioactive nuclides contained in a fusion reactor and a light water reactor, respectively. (Comparaison des risques dus à la toxicité radiologique du tritium et de l'iode-131 qui sont les radioéléments gazeux typiques d'un réacteur fusion et d'un réacteur fission à eau légère.)

3.5 Fusion as a Promising Energy Source for New Millennium

(La fusion: une énergie pleine de promesses pour le nouveau millénaire)

Most of the world energy comes from fossil and fission powers. As discussed in previous two sections, both fossil and fission power is subject to the problem of potential global warming with huge CO_2 emission and potential radiation exposure with RTHP, respectively. These two potential risks are primary causes of the uncertainty of near term world energy supply. As discussed in previous two sections, fusion has a potential advantage over these two major energy sources that two potential risks (global warming and radiation exposure) can be reduced simultaneously as shown in Fig.7.

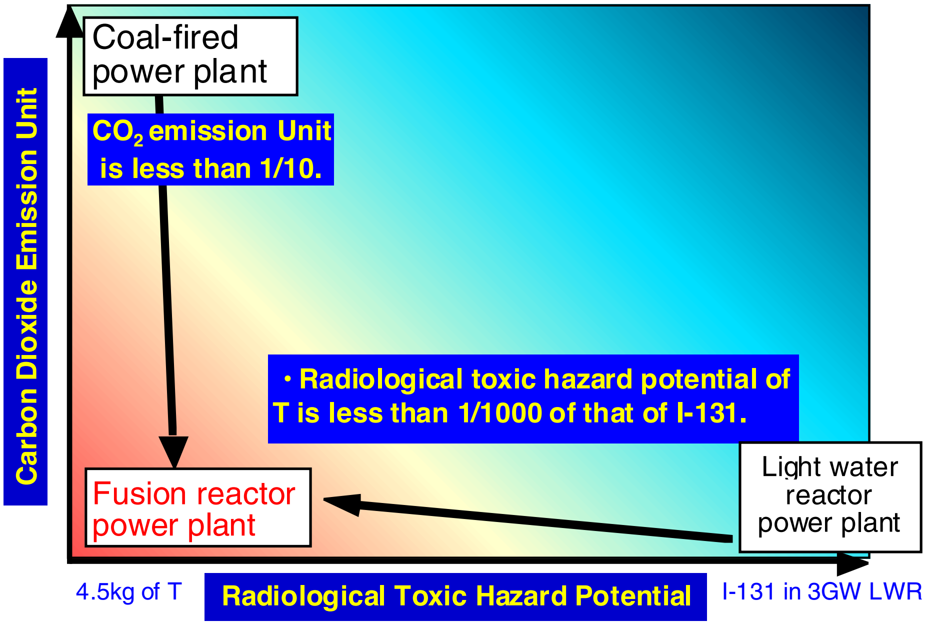


Fig. 7 Two-dimensional quantitative comparison of potential risks between fusion, fission and fossil energy sources. Horizontal axis is the radiological toxic hazard potential of volatile radioactive nuclides as a measure of potential radiation risk to human body. Vertical axis is the

carbon dioxide emission unit as a measure of potential global warming of the climate. (Comparaison sur un graphique à 2 dimensions des risques potentiels des énergies de fusion, fission et d'origine fossile. L'axe horizontal montre le risque radiologique potentiel des radioéléments gazeux, ce risque caractérise le risque radiologique pour les personnes. L'axe vertical montre les émissions de CO_2 qui caractérisent le potentiel de réchauffement global de la planète.)

3.6 Fusion' Merit on Radioactive Waste Disposal

(Avantages de la fusion pour la gestion des déchets radioactifs)

Any human activity is always accompanied by the production of waste. And it is important to take care of the end of the activity. Energy production is associated with the production of wastes such as coal ashes from coal-fired plant and high level radioactive wastes from fission plant. Radiological Toxic Hazard Potentials (RTHP) due to inhalation intake and ingestion intake are evaluated for fission (spent fuel), fusion (tritium and radioactive materials, evaluated for SSTR in section 3.1 and coal-fired plant (coal ashes) [1] as shown in Fig. 8. It should be noted that some radioactive nuclides such as Th-232 and U-238 are contained in coal ashes.

RTHP of fusion for both inhalation intake and ingestion intake becomes smaller by 6 order of magnitude than that of the PWR light water reactor 100 years after the end of plant operation. RTHP of fusion is even smaller than that of coal ashes burned in 30 years.

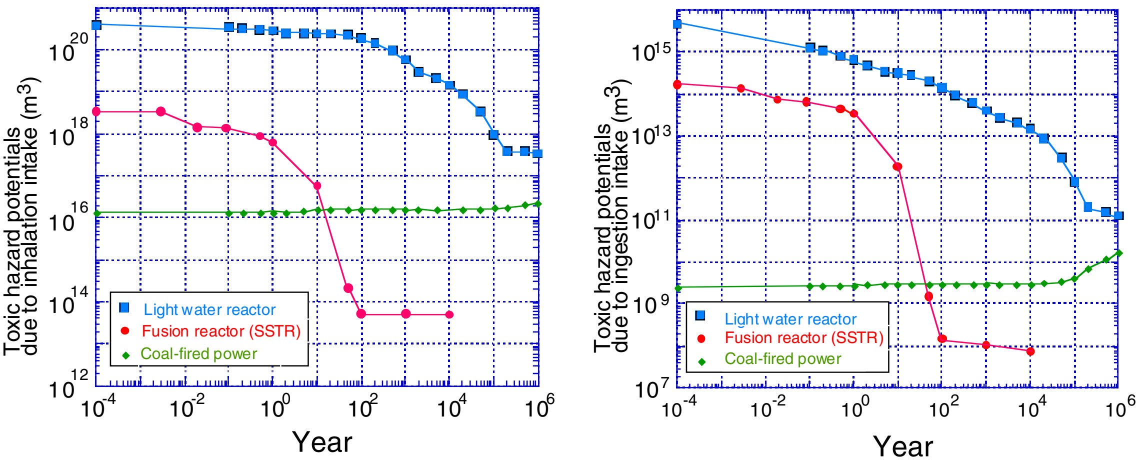
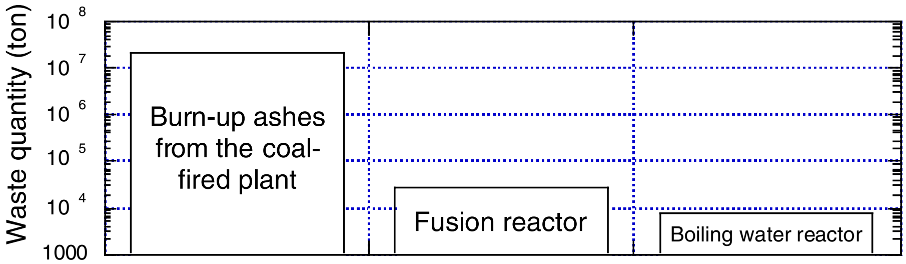


Fig. 8 Comparison of the radiological toxic hazard potentials due to inhalation intake and ingestion intake from a fusion reactor fusion, a light water reactor and a coal-fired. Radioactivity for fusion (tritium and radioactive materials), fission (spent fuel), and coal-fired plant (coal ashes) is calculated for 30 years of operation. (Comparaison des risques de toxicité radiologique dus à l'inhalation et l'ingestion de radioéléments provenant d'un réacteur fusion, d'un réacteur fission à eau légère et d'une centrale au charbon. La radioactivité pour la fusion (tritium et matériaux radioactifs), la fission (combustible irradié), et la centrale au charbon (cendres) a été calculée pour une durée de fonctionnement de 30 ans.)

Disposal cost for radioactive materials is one of important element for commercial use of fusion. Figure 9 shows cost estimates for both fission and fusion power plants [1]. Total disposal cost is estimated to be smaller than that for fission although total weight of waste is larger for fusion.



	High-level radioactive waste	High $\beta\gamma$ waste	Low-level radioactive waste	Total
Fission reactor with 1GW electricity	90 billion yen / 180 m3	3.84 billion yen / 1600 m3	11.7 billion yen / 9750 m3	10.554 billion yen
Fusion reactor(SSTR, 1.08 GW electricity)	-	6 billion yen / 2500 m3	30.12 billion yen / 25100 m3	36.12 billion yen

Used disposal unit prices are low-level waste (¥ 1200000/m3), high $\beta\gamma$ waste (¥ 2400000/ m3) and high-level radioactive waste (five hundred million yen/ m3)

Fig. 9 Comparison of weight of waste for coal ashes, fusion waste and BWR light water reactor. And a comparison of disposal cost for fission and fusion. (Comparaison du poids des déchets des cendres d'une centrale au charbon, d'un réacteur fusion et d'un réacteur fission à eau bouillante. Comparaison du coût de gestion de ces déchets pour la fusion et la fission.)

3.7 Cost Target of Fusion
(Les objectifs de prix pour l'énergie de fusion)

Economical competitiveness is crucial for commercial use of fusion power, even if fusion has many advantages over other energy sources such as low CO2 emission unit, low RTHP during operation and waste disposal. Cost target of fusion was discussed based on various conceptual designs in [1] as shown in Fig. 10. Here, normalised COE (COEn) is defined as COE/COE (coal-fired plant). It is very difficult to predict economical prospect of fusion power. But, fusion could be economically viable if it entered to this target region.

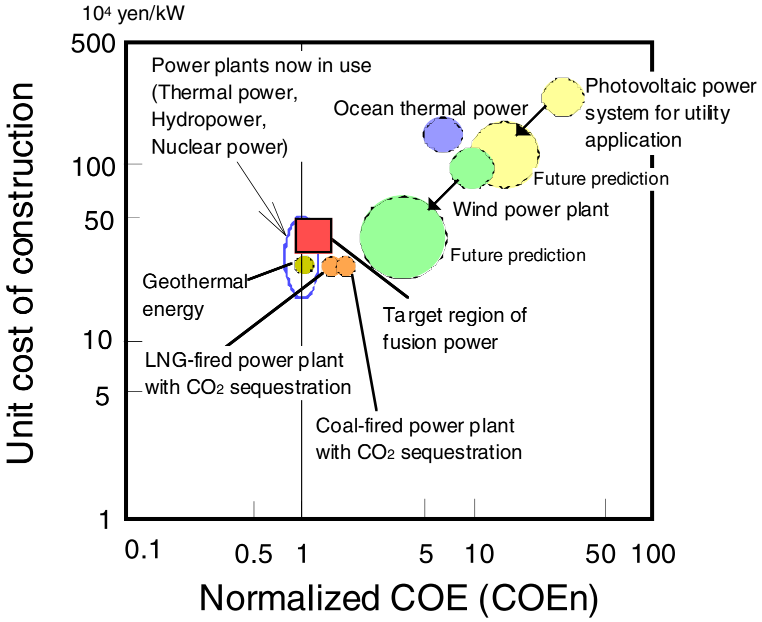


Fig.10 Target region of fusion power plant (COEn=0.7-1.5, construction cost=30-50x10^4 yen/ kWe) and the location of other power plants in the COE (cost of electricity) – construction cost diagram. Values of photo-voltaic and wind are 1994 predicted values [5] while there is more optimistic prediction. Also, small-scale wind power plants exist achieving COEn <2. (Objectifs de coût d'une centrale fusion dans le diagramme : Coût de l'électricité (COE) – Coût de construction (COEn=0,7-1,5, coût de construction=30-50×10^4 yen/kWh). Le diagramme montre la situation d'autres types d'unités de production

énergétique. Les valeurs indiquées pour les systèmes photovoltaïque et éolien datent de 1994. Il existe des centrales éoliennes de petite taille qui obtiennent un COEn<2.)

4. Development Strategy for Realisation of Fusion Energy based on ITER (Stratégie de développement de l’énergie de fusion basée sur ITER)

4.1 Stepwise Approach toward the Realization of Fusion Energy (Un programme par étapes dirigé vers la réalisation de l’énergie de fusion)

Fusion research in Japan is promoted in a stepwise approach based on the "Basic Program" decided by the Atomic Energy Commission. In this stepwise research strategy, clear targets are defined for each step. Transition to the next step should be made when the appropriateness of the next step target and the scientific readiness to proceed to the next step is well assessed. This stepwise approach is being adopted to continuously develop the large-scale, fusion system and to minimize the risk.

The main objective of the second-phase basic program was to establish plasma production and confinement techniques in which fusion power is equal to the auxiliary heating power. This target has been realized in the tokamak device JT-60, which was built as the core device for the second-phase basic program. Key achievements in JT-60 are shown in section 2.

The third-phase basic program is the present fusion development program being pursued in Japan. The main objective in the third-phase basic program is to establish control techniques for the burning plasma (induced by fusion reactions) and to form the technological basis necessary for the development of the fusion Demonstration Reactor (DEMO) to demonstrate the generation of electricity. The tokamak concept was selected for the core device in the third-phase basic program as well as that in the second-phase basic program, although other various confinement concepts have also been intensively investigated. The International Thermonuclear Experimental Reactor (ITER) was adopted as this core device in Japan. Various technologies necessary to proceed to DEMO will be developed in ITER, but one major design guideline is the "single step to DEMO."

Advanced and supplemental research on tokamak devices as well as research on non-tokamak advanced concepts and development of fusion technologies, reactor materials, safety engineering, and fusion power system design are to be performed in the third-phase basic program, in parallel with burning plasma research conducted using ITER. Fusion plasma research for the operation of ITER and to establish high-performance plasma confinement techniques for DEMO should be carried out as advanced and supplemental research in tokamak devices. Major research themes are the establishment of steady-state operation, suppression of disruptions, realization of low-temperature divertor plasma, improvement of plasma confinement, etc.On the other hand, based on non-tokamak advanced concepts, other magnetic confinement systems, such as helical, reversed field pinch, compact torus, mirror, spherical torus, and inertial confinement systems are being studied.

Engineering issues of various fusion technologies required for the development of the DEMO reactor are being solved through the ITER program. However, the neutron flux in ITER is insufficient for testing blanket structural materials to be used in the steady-state fusion DEMO reactor. Therefore, it is necessary to construct the 14-MeV neutron source and test heat-resistant, low-activation structural materials.

This 3rd phase basic program is schematically shown in Fig.11.

The step after the third-phase basic program is the fusion Demonstration Reactor phase (DEMO), which has the principal objective of the engineering demonstration of electricity production by fusion power. Electricity production in a large-scale fusion power plant will be realized for the first time in this phase. The confinement concept for this phase will be decided based on the investigation of the tokamak type DEMO study and the performance of other confinement concepts at the transition from the third-phase basic program to this phase.

The step after the DEMO phase is the commercialization phase. If economic feasibility is demonstrated in this phase, fusion power will be qualified to penetrate the energy market as a commercially competitive option. The government will retain leadership through the DEMO phase, but the commercialization phase will be led by the private sector. Therefore, the prospects for commercialization should be firmly established by the DEMO phase.

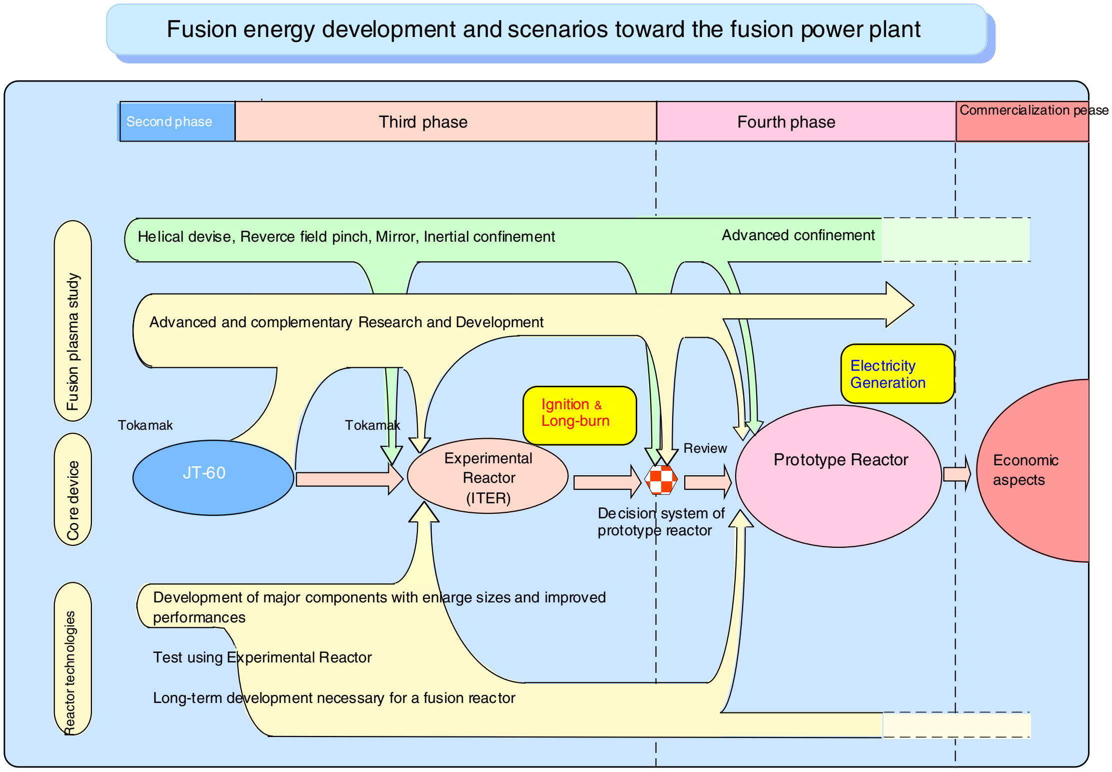


Fig. 11 Schematic view of third phase basic program of fusion research and development in Japan (Schéma de la 3^{e} étape des recherches sur la fusion au Japon)

4.2 Control of burning plasma and technologies addressed in ITER (Contrôle du plasma thermonucléaire et développement technologique dans ITER)

Design and R&D have progresses since the initiation of Conceptual Design Activity (CDA) in 1988. Engineering design of ITER has progressed [7] and its Final Design report is under preparation for the decision of construction. Self-heating power produced by the fusion reaction will be applied to the burning plasma in ITER, while only plasma heating from the external sources has been examined in experiments to date. It is difficult to predict burning plasma behavior with the present knowledge base since fusion self-heating simulation using external power is difficult. Therefore, without understanding this burning plasma behavior, it is difficult to clearly predict the technical feasibility of fusion energy. Nonetheless, fusion energy development can be achieved by advancement of existing technologies if the control of burning plasma becomes possible. Thus, the understanding and control of burning plasma is the last big challenge of fusion energy research.

Plasma is controlled by a magnetic field. The controllability of burning plasma can be proven by demonstrating that the plasma can be sustained stably for a period long enough for the magnetic field to penetrate into the whole plasma. For ITER, this period is 300-500 seconds.

The size of the experimental device and the strength of the magnetic field to satisfy these conditions have been defined using information accumulated in the non-burning plasma databases. The database applicability can be confirmed in the experimental reactor itself. Once confirmed, the design of the DEMO and the commercial fusion reactors becomes possible.

The principal experimental objective of ITER is the production and control of burning plasmas. To achieve this objective, new technologies and facilities are necessary. There are number of requisite technologies, such as large super-conducting magnet [8], plasma heating technology, blanket technology to breed tritium (which is rare in nature), tritium handling technology, radiation shielding technology, radioactive material disposal technology, remote maintenance technology, heat removal technology, and power and particle handling technology from the high-temperature plasma. Furthermore, system technology to integrate these technologies and associated facilities as well as to assure a high level of safety and reliability is required [9]. A major milestone for these technological developments, which are indispensable for the DEMO reactor, is the construction and application of ITER.

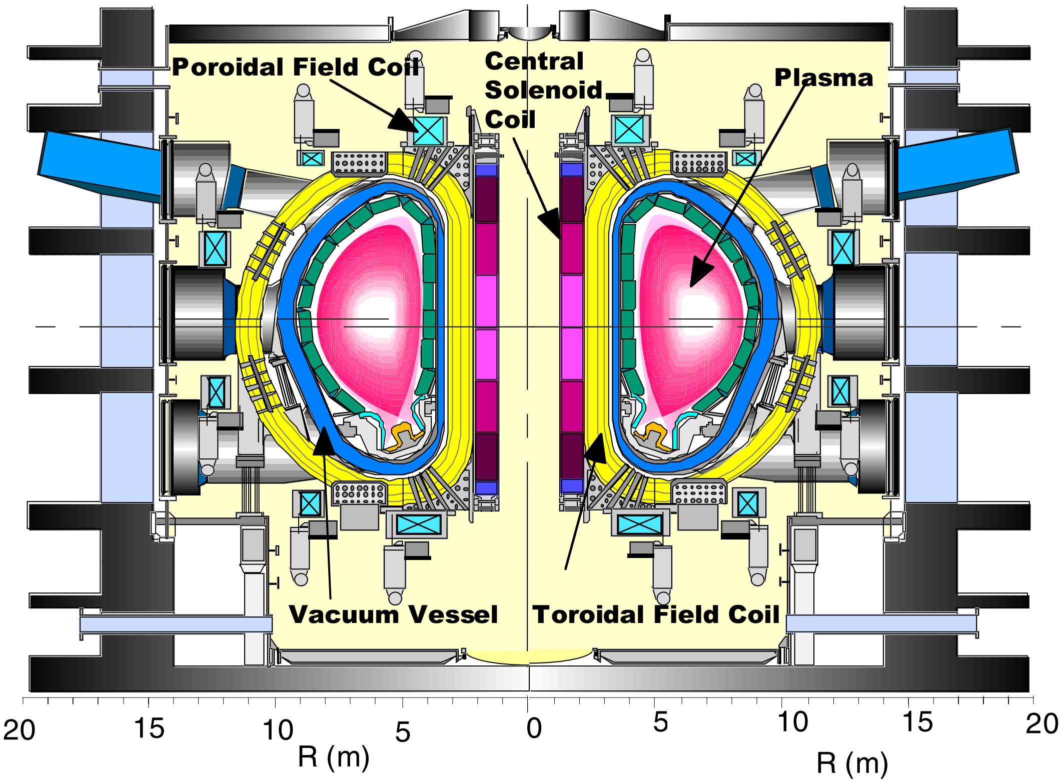


Fig. 12 Cross sectional view of ITER. Deuterium-Tritium fusion reaction takes place in the plasma (major radius Rp=6.2m, minor radius ap=2.0m). Plasma is surrounded with in-vessel components (divertor and shield blanket) and vacuum vessel. Large current is flowing inside the plasma (Ip=15MA) forming magnetic field for plasma confinement. Other magnetic fields are produced by central solenoid coils, poloidal field coils, and toroidal field coils. (Section d'ITER. Les réactions deutériun-tritium ont lieu dans le plasma (grand rayon R_p=6.2 m, petit rayon a_p=2 m). Le plasma est entouré par les composants de la première paroi (diverteur et couverture) et est contenu dans la chambre à vide. Un courant électrique de 15 MA circule dans le plasma et crée des composantes de champ magnétique pour le confinement. D'autres champs magnétiques sont produits par le solénoïde central, les bobines de champ poloïdal et les bobines de champ toroïdal.)

Technologies required for DEMO should be developed in parallel with those needed for ITER. By confirming them in ITER, one major ITER design guideline, a "single step to DEMO," can be realized. Major issues of concern are discussed below.

(1) Development of steady-state operation scheme
The basic principle of steady-state operation in tokamaks is shown in Fig. 13 and it has been proven at a number of research institutions in Japan and other countries. It is important to fully develop steady-state operation methods through the most productive use of existing tokamak facilities and to apply their performances to ITER operation, especially to the burning plasma in ITER. At the same time, it is important to establish operational methods that avoid plasma disruptions, which preclude steady-state operation.

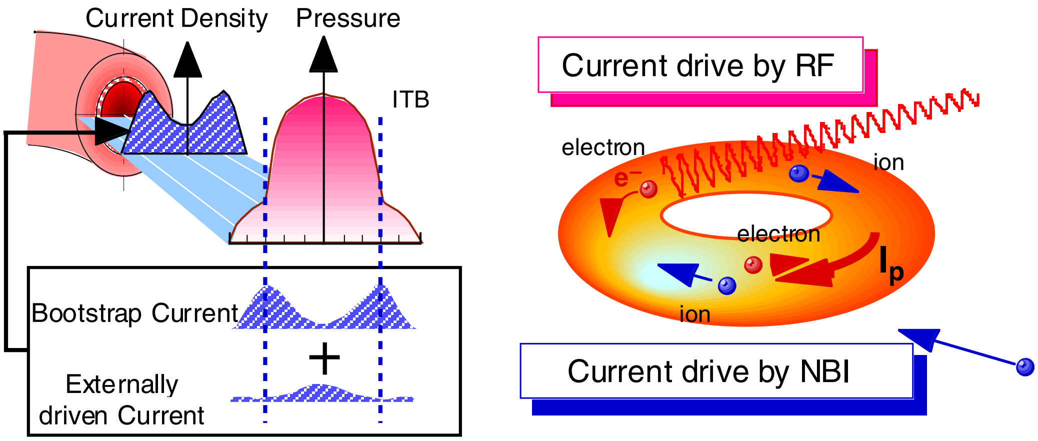


Fig. 13 Basic principle of steady-state operation in tokamak and possible candidates of external current drive by RF and NB. Bootstrap current is a pressure driven current. (Principes de base du fonctionnement en régime continu d'un tokamak et représentation des technologies de radio-fréquence et d'injection de neutres qui sont candidates pour maintenir le courant du plasma. Le courant du type "bootstrap" est crée par la pression du plasma.)

(2) Development of high-temperature blanket test modules

The blanket plays three important roles, neutron shielding, tritium breeding, and extraction of high-temperature thermal energy as shown in Fig. 14. The latter will produce steam for generation of electricity. To accomplish the technologies relevant to these roles, a high-temperature blanket is required. Developed in ITER, its design will be available for DEMO.

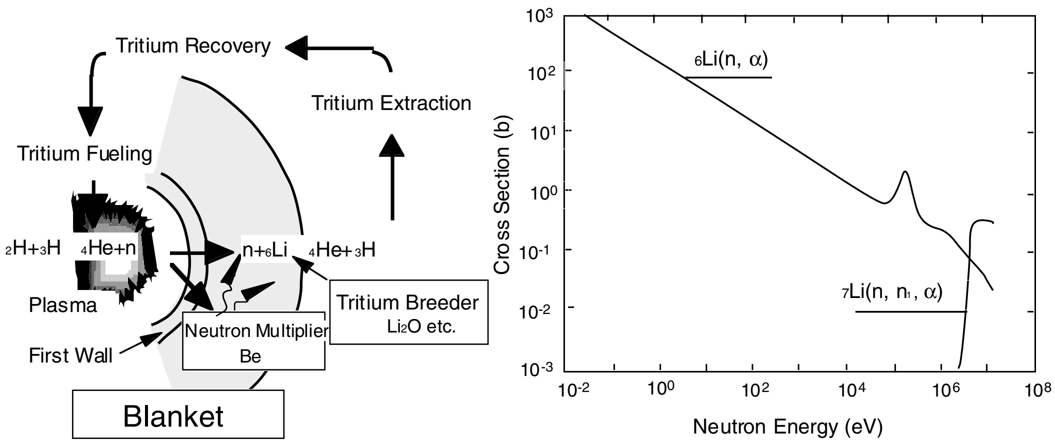


Fig. 14 Schematic view of the function of blanket and the cross section for n-Li reaction. (Principe de fonctionnement de la couverture et section efficace pour la réaction n-Li.)

(3) Neutron irradiation test

Development of reduced activation materials that allow intense high-energy neutron irradiation and high-temperature operation is required to enhance safety and economics of fusion. Leading candidates for blanket structural materials to be used in DEMO and beyond have been identified as shown in Fig. 15. However, performance of these materials should be confirmed by neutron irradiation tests, as the material database has not been satisfactorily completed at present. Neutrons produced in ITER can be used for irradiation tests at low fluence and for component tests.

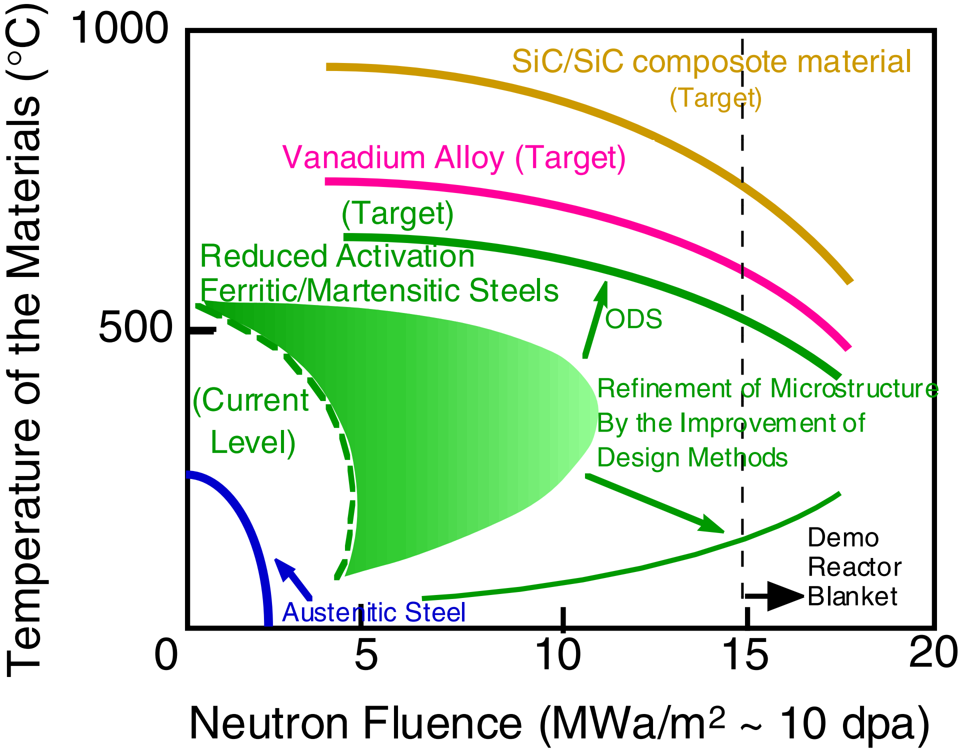


Fig. 15 Performance extension and target performance of candidate blanket structural materials in operating temperature and neutron fluence. There are three candidates for blanket structural materials. (Domaines de fonctionnement et objectifs de performances en température et flux intégré de neutrons pour les matériaux de structures de la couverture. Il y a trois matériaux candidats pour la structure de la couverture.)

4.3 Prospect of commercial fusion power generation from ITER
(Les perspectives commerciales de l’énergie de fusion après ITER)

A fusion reactor that generates electric power with repeated pulses, each having a duration of a few to 10 hours, is technically feasible using ITER technologies--provided the long burn is realized in ITER. From the present perspective, such a reactor tends to be large in size and not economically advantageous.

Construction of the tokamak DEMO reactor having steady-state operation as shown in Fig.16 will become possible when the preparatory research on technologies required for the DEMO reactor, i.e., steady-state operation technologies and high-temperature blanket technologies, are developed in ITER. The construction and operation of the DEMO reactor will demonstrate the technical feasibility of fusion energy. The DEMO reactor is to be a prototype of a commercial fusion reactor and will complete the research and development phase of fusion reactor technology.

Fusion must be economically competitive with other energy sources to enter the energy market. Reduction of the reactor size, the cost of maintenance, and the frequency of inspection and replacement, as well as the attainment of steady-state operation of the reactor and further improvements in plasma performance are vital to enhance the economic competitiveness of commercial fusion power reactors.

Development of low-activation materials and high-strength field magnets as well as the improvement in plasma confinement performance will be effective in reducing the size of the reactor. Proposed candidate low-activation materials have been selected and an irradiation test of these materials with the14-MeV neutron source is necessary. A good prospect has been identified for the manufacture of higher strength field magnets than those of ITER. An engineering demonstration is such a high-strength field magnet is envisaged.

Periodic replacement of the structural materials during the lifetime of a fusion reactor is necessary due to the irradiation damage caused by energetic neutrons. Effective approaches to reduce the cost of electricity are to extend the period between replacement of components by the extension of material lifetimes and to reduce the replacement times required. The former will be realized by the development of high-performance materials, and the latter will be accomplished by the improvement of maintenance procedures.

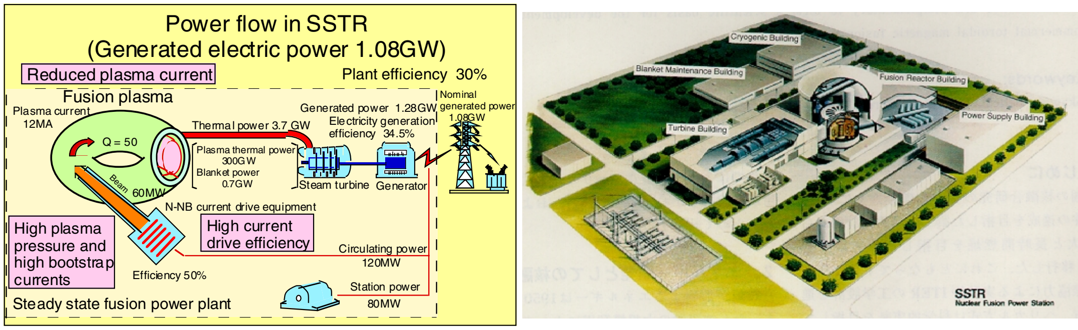


Fig. 16 Example of energy flow and plant layout in a steady-state tokamak fusion reactor. (Flux d'énergie et exemple d'implantation d'un réacteur fusion du type tokamak fonctionnant en régime continu.)

Reducing the cost of electricity produced using a magnetic confinement system will be effectively be achieved by confining the plasma at high pressure, namely, by realizing the confinement of the high-performance plasma. Research on the improvement of fusion plasma performance, in other words, confinement of high-performance plasma, should be continued even after the realization of fusion electric power generation. The research results obtained will contribute to improving economic attractiveness.

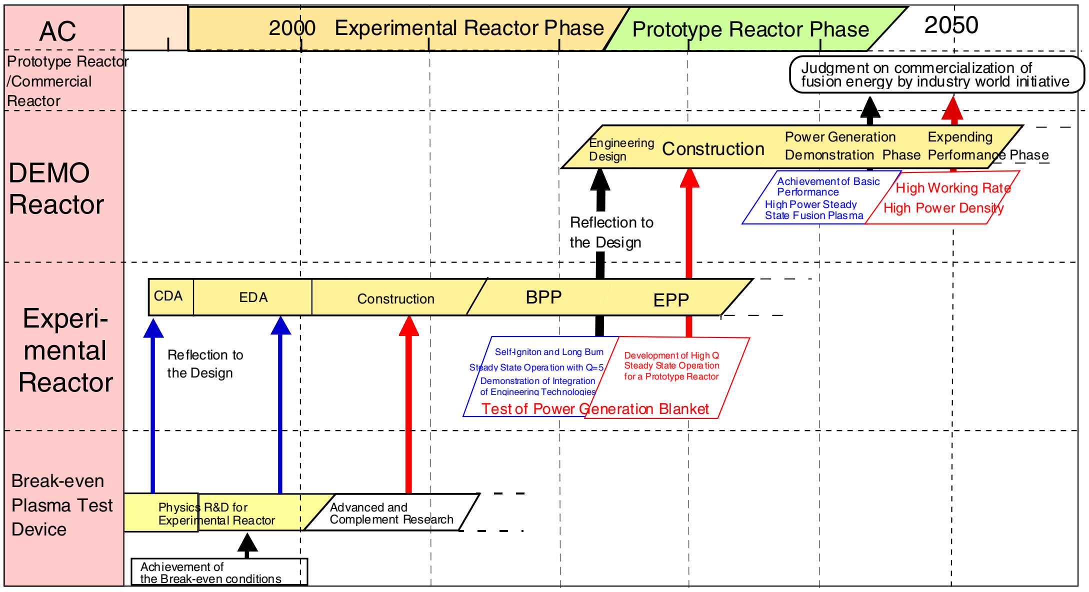


Fig. 17 An example of the development schedule of tokamak fusion power. (Exemple du calendrier de développement de l'énergie de fusion produite par les Tokamak.)

From a technical point of view, power generation by the DEMO reactor would be possible around 2040--if developments in technology progress as they are doing at present and if achievements in ITER are incorporated into DEMO. It is expected that more than 10 years will be required after the DEMO reactor is operating satisfactorily for fusion power to be recognized as a commercially available option having economic competitiveness. An example of the development schedule of tokamak fusion development program is shown in Fig. 17. An accurate prediction is difficult, as it depends on the progress of innovative technology, on the economic features of other energy sources, and on mid-century social conditions.

4.4 Technical Feasibility of Fusion Energy
(La faisabilité de l'énergie de fusion)

The technical feasibility of fusion energy will be confirmed by demonstrating control of burning fusion plasma, by establishing the technical feasibility of an integrated fusion device, and by accomplishing safety and reliability in ITER. Furthermore, a high-performance fusion reactor will be realized by establishing steady-state operation. Most major technologies required for the DEMO reactor and beyond can be developed as an extension of ITER. Therefore, the prospects of fusion development for the DEMO reactor and beyond will become clearer during the ITER program, as compared to the present situation where clarification of physical phenomena receives more emphasis. In addition, it is possible that the construction cost of the DEMO reactor will be lower than that of ITER due to development of materials, technological innovations, and the progress of plasma physics. A similar possibility could apply to a commercial fusion power station that would follow DEMO.

Finally, we understand that the fusion energy development is now entering the new step. And the construction and operation of ITER through international co-operation is an important step towards the realization of fusion energy for the new millennium.

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