＜論　　説＞

The Way of ITER

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This article investigates possibility of ITER for human society. The author visited ITER's site in Saint-Paul-lès-Durance located in south- eastern France, on February 25, 2022 (See *Note -1*). The investigation of ITER in this article is based on an interview with the director of the ITER project and reference books.

Initially ITER was an acronym for International Thermonuclear Experimental Reactor. Today, ITER officially means "the Way" or "the Pass" in Latin. The ITER project is the largest international experiment conducted to generate energy through the fusion of deuterium and tritium. As the fusion process is similar to that of the Sun, the project is called "The Sun in the Ground." The fusion process does not generate high levels nuclear waste or carbon gas. Moreover, regarding energy resources, deuterium exists in sea-water, and tritium can be collected after the fusion process.[1]

Here, we investigate the history and future possibility of this large international cooperative project.

1. The History of ITER

The first opportunity to launch ITER come with the invention of Japan Atomic Energy Research Institute Fusion Torus-2 (JFT-2,) the Tokamak Research Installation in Japan, in 1972. From 1978 to 1988, the International Tokamak Reactor project was developed through the cooperation between the USSR, the European Atomic Energy Community, the United States, and Japan.[2]

In the Experimental Power Reactor (EPR) stage, various R&D activities were necessary. Hundreds of atomic scientists from various countries participated in the R&D process regarding a detailed assessment of the fusion process, tokamak confinement system, and design for harnessing nuclear fusion energy.

M. Gorbachev met with French President F. Mitterrand in October and with U. S. President R. Reagan in November 1985 at the Geneva Summit. They confirmed the potential importance of work aimed at utilizing thermonuclear fusion for peaceful purposes.[3]

In October 1986, at the Reykjavik Summit, the “Quadripartite Initiative Committee” of the Euratom countries in Europe, Japan, the USSR, and the United States was organized.

In March 1987, the Quadripartite Initiative Committee visited the International Atomic Energy Agency (IAEA) headquarters in Vienna, Austria. They discussed the legal foundation for the peaceful use of fusion technology, organizational problems, staffing affairs, and the project location. Based on these discussions, the ITER project was launched in 1988.[4]

Between 1988 and 1990, at conceptual design activity (CDA) project was developed. In 1992, EU countries, Japan, Russia, and the United States, established their original technological objectives. Engineering Design Activities (EDA) began in 1998.

From 1999 to 2003, the United States temporarily exited the ITER project because of its decision to focus on the National Ignition Facility project, which was concerned with a laser fusion system oriented toward military technology. However, as the fundamental technological problem expanded the project budget, it returned to ITER in 2003.[5]

China and South Korea participated in the ITER project in 2003, and India joined in 2005. In 2005, the ITER site was located in Saint-Paul-lès-Durance in Cadarache. In the last stage of local selection, two villages-, Saint-Paul-lès-Durance in France and Rokkasho-mura in Japan,- competed against each other. The EU, China, and Russia supported Saint-Paul-lès-Durance, whereas Japan, the United States, and South Korea preferred Rokkasho-mura. Then, as France proposed favorable conditions concerning budgets and personnel affairs to Japan, Saint-Paul-lès-Durance was selected.[6]

Table -1. ITER Chronological Table of Events

Date	Event
1985	Geneva Summit: agreement regarding the importance of fusion technology for peaceful purposes
1986	Reykjavik Summit: establishment of the original committee- Europe, Japan, USSR, the United States
1988	ITER project officially initiated.
1988-1990	CDA project is developed
1992	Original technical objectives established
1998	EDA completed (EU, Japan, Russia, USA)
1999	USA exits
2003	USA returns, China and Korea join
2005	India joins, Saint-Paul-lès-Durance selected as the site of ITER
2008	Start of ITER formation
2013	Tokamak complex construction starts
2015	Tokamak construction starts
2018	Assembly and integration
2025	*Operation of prazuma*
2035	*Deuterium and tritium operation*

2. ITER's Mechanism and Objectives

The Fundamental scientific concept of the ITER is the fusion of deuterium and tritium. This fusion produces helium nuclei and high-energy neutrons. Theoretically, the fusion reactions are similar to those of H-bombs. The final practical objective of a peaceful nuclear fusion project is the production of electrical energy. There is a long technological hierarchy process, which implies a means-ends process of problems and solutions. R&D processes involve fundamental research via applied research and core technology in the development stage of a practical product.[7]

Core technology of nuclear fusion

Nowadays, there are two main types of core nuclear fusion technology: joule (ohmic) heating using the magnetic field confinement method and laser fusion using the inertial confinement method.[8] Moreover, the magnetic field confinement method is divided into two subtypes of core technology: the tokamak and the helical method. ITER employs the joule heating and magnetic field confinement using the tokamak method. In the latter, a round electric coil binds helically the vacuum vessel of the plasma.[9]

As mentioned above, the United States conducted research on laser nuclear fusion in the early 1990s. Laser nuclear fusion R&D continue in the United States, Japan, and Europe. The next section describes the technological hierarchy of the nuclear fusion process based on two core concepts: Joule and laser heating.

In general, fusion reactions require extremely high temperatures because of the strong electrostatic repulsion between two protons, that have the same positive charge. Deuterium and tritium are the most attractive isotopes because their fusion reactions require the lowest temperatures. Even though the lowest temperature, higher than 100 million ℃, is necessary for the fusion process.

At ITER, the plasma will be heated to 150 million ℃ by joule heat (ohmic heating), with an electric current passing through the plasma. Theoretically, the heating mechanism is similar to that of an electric stove and its range. Additional heating is supplied using natural beam injection and radio frequency (RF) or microwave heating, which has the same mechanism as that of a microwave oven.[10]

Moreover, the fusion reaction requires stable confinement of the plasma as the particles are exceedingly kinetic at such high temperatures. ITER uses a central solenoid magnet, poloidal magnets around the edges of the tokamak, 18 doughnut- shaped toroidal-field (TF) coils, and correction coils.[11]

The construction of the18 large TF coils is important for completing the ITER project. The TF coil is superconductive and has a 16.5 m height, 9 m width, and a weight of 300 t. Nineteen coils are built, including a spare. Eighteen TF coils encircle the vacuum vessel. These core technological parts are produced by the EU（14 coils）and Japan（5 coils）. The inner walls of the TF coils are manufactured by Mitsubishi Heavy Industries. After constructing the large tokamak equipment, the final acceptable errors are less than 2 mm for the out-board and 1 mm for the in-board.[12]

Objectives of ITER

Although the long-term objective of nuclear fusion R&D is electric power generation, ITER focuses on scientific research and technological demonstrations without electricity generation. The objectives of ITER are summarized as achieving significant fusion energy, developing plant operations including heating, cryogenic cooling systems, remote maintenance through robot systems, tritium breeding, and establishing the total safety of a large fusion plant.[13, 14]

In 1997, the Joint European Torus（JET）established champion data for a maximum instantaneous energy of 16,000 kW using nuclear fusion. However, practical power generation requires hundreds of thousands of kW. The ITER is expected to yield 500,000 – 700,000 kW.

The fusion energy gains factor（Q）is the energy difference between the input and output. Q ＝1 indicates that the input and output energies are equal, which is referred to as the scientific breakeven point. In 2022, the National Ignition Facility reactor achieved a Q value of 1.5. ITER aims to attain Q values equal to 10, producing a fusion plasma with thermal power 10 times greater than the injected thermal power.[15, 16]

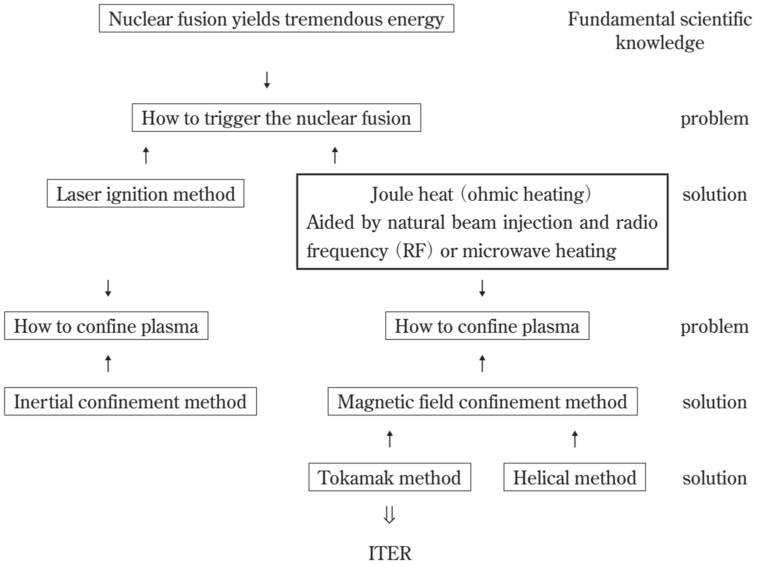
Moreover, sufficient stable confinement of the plasma for 300–500 s is necessary for nuclear fusion. The confinement champion data of the high-pressure-plasma is 55 s according the Korea Superconducting Tokamak Advanced Research. The champion data of low-press- plasma confinement is 5 h 16 m by the Tokamak of the Research Institute for Applied Mechanics（TRIAM）at Kyushu University, Japan. Practical operation requires at least 300–500 s confinement of high-press-plasma.[15]

3. Technological Hierarchy of Nuclear Fusion

The starting point of the technological hierarchy of nuclear fusion is scientific knowledge: nuclear fusion creates tremendous energy, which is three times greater than the U-235 fission energy, and 1 g of fused helium yields the same energy as that of 8 t of oil.[17, 18]

Figure -1 describes the technological hierarchy of nuclear fusion energy production, which begins with the fundamental scientific knowledge of nuclear fusion phenomena. The first problem is

Figure -1 Technological hierarchy of nuclear fusion



how to trigger nuclear fusion by overcoming the strong electrostatic repulsion between the two protons. Two types of trigger solutions are the core technologies for the nuclear fusion process.

The second problem is plasma confinement. There are solutions to confine plasma such as inertial and magnetic field confinement methods. Moreover, there are two types of magnetic confinement methods: tokamak and helical methods.

These problems and solutions, that is, the means-end analysis process, developed from fundamental science and technology to practical technology through applied research and engineering, construct a technological hierarchy.[19]

Future of nuclear fusion

Nuclear fusion energy production has various positive expectations, such as enormous amount of energy from unlimited resources without high-level atomic- contaminated waste. Deuterium can be extracted in unlimited quantities from sea-water, whereas tritium is a rare element that can be bred through nuclear fusion reactions. Therefore, tritium- breeding technology is inevitably important for the ITER project.

Tritium can be bred in 440 “blanket” modules that completely cover the inner walls of the vacuum vessel. The ITER blanket modules cover the surface of the inner wall directly facing the hot plasma and store tritium owing to its unique physical property; during the last stage of the ITER operation, some of the blanket modules will be replaced, and tritium will be extracted from the blanket. The ITER will test the essential concept of tritium self-sufficiency.[20] All of the critical inner wall equipment includes a diverter, which protects the vessel from high-temperature plasma. Efficient cleaning is supplied by Mitsubishi Heavy Industry.

Through the realization of the tritium self-sufficiency process, tritium will become an inexhaustible resource, as will deuterium., Similar to other nuclear fusion projects, the ITER project pursues large amount of electric energy using unlimited resources. A supervisory officer of ITER mentioned that after ITER technology, wars of struggle for limited fossil fuels such as coal, oil, and gas ceased.[21]

Furthermore, ITER does not discharge high-level radioactive waste or poisonous gases, such as Nitrogen Oxides or CO_2. If the ITER project were successful, constructing a large nuclear –waste storage site by ANDRA (Agence Nationale pour la gestion des Déchet Radioactifs)[22] would not be necessary. However, humans with limited rationality unavoidably seek technological developments in both nuclear fission and fusion because of uncertain predictions.

4. Cooperation for a Future Beyond Current Conflicts

The ITER core member countries (27 EU countries, Russia, Japan, the United States, China, Korea, and India), cooperate with Switzerland and the United Kingdom through Euratom. In total, 35 countries are participating in the ITER project. The EU is responsible for the largest percentage (46.6%), and other core countries contribute the remaining 53.4% to the ITER project. Most member countries' contributions are delivered to the ITER project in the form of completed components, systems, or buildings, rather than monetary contributions.

Although there are some serious international conflicts in the current world, ITER, as an international cooperation project, aims to maintain the development of solutions to a common future energy problem. The Russo-Ukraine War began on February 24, 2022, when I visited Saint-Paul-lès-Durance. The following day, I visited ITER, and the supervisory officer explained that the ITER project had successfully navigated through various international conflicts (*See Note –2*).

Since the Russo-Ukraine War, the world has been roughly divided into liberal countries such as Europe, the United States, and Japan and totalitarian countries such as Russia, China, Iran, and North Korea. These two camps have experienced continuous economic and political conflicts related to trade and military competition. However, Russia and China have been cooperating with liberal countries in the ITER project.

International criticism

There is another conflict stemming from the criticism of the project. Various international environmental groups are against the ITER project for two main reasons.[23] First, the extremely large nuclear fusion operation will threaten the environment, with the risk of large- scale accidents. Second, not all physicists and engineers are familiar with the novel phenomena and technologies of nuclear fusion and plasma.[24]

However, nuclear fusion physicists and engineers insist that they analyze fusion reactions and plasma phenomena in detail. Moreover, they emphasized that ITER never discharges high-level radioactive waste and thus has less accident possibility. As ITER discharges only helium gas and low-level nuclear waste, its operation does not seriously influence the environment.

Concerned with the possibility of an accident, they explained that the nuclear fusion reaction is inclined to stop without continuing heat, while nuclear fission cannot be limited without cooling.[25] Nuclear fusions, similar to an automobile, easily stop without acceleration, while nuclear fission is compared to an automobile accelerating without continuing to brake. Therefore, an accident involving the ITER cannot occur easily.

Furthermore, because unlimited deuterium and self-supported tritium supply inexhaustible fuel resources, the ITER project could terminate the international struggle for fuel.

5. Conclusion

Nuclear fusion is an ideal technology for generating electric energy through the fusion of deuterium and tritium because it does not generate high-level nuclear waste or carbon gas and provides unlimited energy resources. Deuterium is inexhaustible in seawater, whereas tritium can be extracted from ITER blanket modules after fusion. Moreover, the high security of the nature of the nuclear fusion reaction is favorable because it is inclined to stop without continued heating, whereas the nuclear fission process cannot be stopped without cooling.

Although the ITER project may become practical in the future, it still has a long way to go. As international environmental groups insist, ITER systems are extensive. Furthermore, scientists or engineers are unfamiliar with several phenomena, such as plasma, because of their uncertainty. Accidents involving large equipment can be catastrophic.

However, intuitively, scientists or engineers are unfamiliar with any new technology at any point in time. Furthermore, we must consider the "law of concomitance between technological risk and performance".[26] Today, we can enjoy our civilized society only after numerous challenging technological innovations across centuries, and we can achieve high-tech performance with proportional risk.

Note –1

On February 24, 2022, I visited Saint-Paul-lès-Durance, and the ITER's site on February 25.

Supervisory Officer Ohmae outlined the ITER project. After our discussion, a member of the personnel guided me through the construction field at Tokamak.

Note -2

Supervisory Officer Ohmae insisted that not only liberal countries' but also totalitarian countries' scientists and engineers maintained their solidarity to create future brilliant energy innovation, despite actual international conflicts. Organizational problems and management theories are more crucial than scientific and engineering theories in sustaining cooperative relationships among personnel from various countries.

Bibliography

1) Inoue, N. et al.『核融合実験炉 ITER の進展』技術経済研究所　第2章　2003 *Nuclear Fusion Experimental Reactor*, Institute for Techno-economics Chap. 2, 2003
2) Japan Atomic Energy Agency, *Nuclear Renewable*, 1972
3) Arnoux, R. "Conceived in Geneva, Born in Reykjavik, Baptized in Vienna" *ITER Newsline*, 2021
4) Bonner, E. "ITER Initiative" *Euro Fusion*, 2005
5) Ball, P. "Laser fusion experiment extracts net energy from fuel" *Nature News*, 2014
6) Brumfiel, G. "Europe beats Japan to ITER prize" *Physics World*, 2005
7) Oyama, K. See the Chap.1,『技術革新の戦略と組織行動　増補版』白桃書房 *Technological Innovation and Organizational Behavior Augmented Version*. Hakuto-shobo Press, 1998
8) Inoue, N. et al. op. cit. Chap.1, 2003
9) Inoue, N. et al. Ibid. Chap. 3, 2003
10) ITER "Reaching 150,000,000℃" https ://www.iter.org/sci/PlasmaHeating
11) Inoue, N. et al. op. cit. Chap.3, 4, 5, 2003
12) Ohmae, Supervisory officer of ITER, based on the interview on Feb. 25, 2022 in Saint-Paul-lès-Durance
13) Inoue, N. et al. op. cit. Chap. 4, 2003
14) Brans, P. "What is a burning plasma?" ITER organization 2021
15) Inoue, N. et al. Ibid. Chap. 1, 2003
16) "Facts & Figures" http://www.iter.org/factsfigures 2017
17) Itoh, S. et al.「超伝導定常トカマク TRIAM・1M とその成果」"Superconducting Steady State Tokamak TRIM・1M" *Journal of Nuclear Science and Technology, Vol. 31 No. 6*, 1989　Atomic Energy Society of Japan
18) National Institutes for Quantum Science and Technology,「先進プラズマ研究」"Advanced Plasma Research" 2021
19) Oyama, K. op. cit. 1998
20) Inoue, N. et al. op. cit. Chap. 5, 2003
21) Ohmae, Supervisory officer of ITER, Based on the interview on Feb. 25, 2022 in Saint-Paul-lès-Durance
22) Based on author's observation of ANDRA's site in Bure on February 28, 2022
23) Jassby, D. "ITER is a showcase for the drawbacks of fusion energy" *Bulletin of the Atomic Scientists*, 2021
24) Lerner, J. "What are the fastest routes to fusion energy?" *Physics of Plasma* 2023
25) Ohmae, Supervisory officer of ITER, Based on the interview on Feb. 25, 2022 in Saint-Paul-lès-Durance
26) Oyama, K. "Nuclear Power Technology in Post-Industrial Civilization", FFJ https://hal.science/hal-03737847v1/document, 1.1, 2022