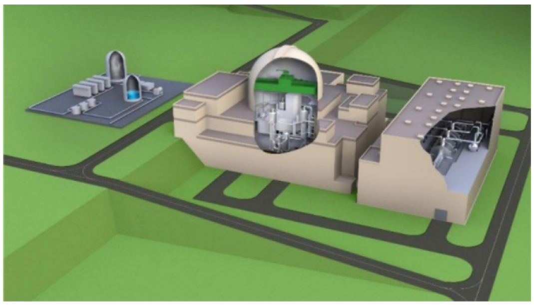
Contribution to Carbon Neutrality by Nuclear Energy



YURUGI KANZAKI[*1] JUNICHI NISHITANI[*2]

TAKAAKI KITAGAWA[*2]

Nuclear energy is a carbon-free, large-scale, and stable power source and an important baseload power source from the viewpoint of energy security. Therefore, we recognize that continuous usage of nuclear energy is essential in order to achieve carbon neutrality in Japan by 2050. Mitsubishi Heavy Industries, Ltd. (MHI) is supporting electric utilities for the restart of existing plants in Japan and the early completion of the construction of specialized safety facilities, along with supporting the early establishment of the nuclear fuel cycle. Furthermore, MHI is developing an advanced light water reactor "SRZ-1200" that will ensure the world's highest level of safety, and also developing various other types of reactors to meet a diverse set of societal needs in the future. This report describes efforts within our nuclear energy business and associated efforts to ensure achievement of carbon neutrality by 2050.

1. Introduction

In October 2020, the Japanese Government announced that the country would aim for "carbon neutral by 2050" to ensure alignment with the global response to climate change. In ongoing efforts to decarbonize, the recent Russian invasion of Ukraine has led to a sharp rise in resource prices, which has revealed energy security risks worldwide. Also in Japan, the importance of stable power supply has been highlighted by the nation's first warning of a power supply and demand crunch issued in March of 2022.

Achieving both decarbonization and a stable energy supply are once again recognized as important issues. Renewable energies such as solar and wind cannot maintain a stable power supply. These forms of renewable power generation depend on seasonal and weather conditions. Conversely, nuclear energy is a large-scale, stable power source that does not emit CO_2 during operation and is not affected by weather conditions. In addition, it has the ability to work alongside and complement output fluctuation of renewable energy sources such that a diverse energy generation mix can be achieved. MHI is working from short-, medium-, and long-term perspectives to ensure achievement of carbon neutrality and a stable power supply in the future based on our cultivated nuclear energy technology.

2. Roadmap for nuclear energy toward achieving carbon neutrality

Nuclear energy is a technologically proven carbon-free, large-scale, and stable power source and an important baseload power source which ensures energy security for society. Continuous usage of nuclear power is essential for the achievement of carbon neutrality by 2050.

However, since the Great East Japan Earthquake, the public's confidence in nuclear energy declined and we recognize that restoring that confidence is one of the most important issue to overcome. As the only one manufacturer for pressurized water reactor (PWR) plants in Japan, we have proactively supported Japanese electric power companies with restarting of existing domestic plants and thus far have successfully supported the restart of 10 PWR plants. We will continue to provide support for all other PWR restarts which occur along with ensuring the successful completion of specialized safety facilities. Even though we are not the manufacturer for Japan's boiling water reactor (BWR) plants, we have proactively been working with Japanese electric

*1 General Manager, Nuclear Systems Engineering Department, Nuclear Energy Systems, Mitsubishi Heavy Industries, Ltd.
*2 Deputy Director, Nuclear Systems Engineering Department, Nuclear Energy Systems, Mitsubishi Heavy Industries, Ltd.

power companies to apply our lessons learned and knowhow to ensure a successful restart of these plants. These efforts show our commitment to ensure Japan realizes stable electricity supply, decarbonization, and most importantly restoration of public confidence in our industry. Additionally, our expectation is that we use nuclear energy sustainably over the long term and to achieve this establishment and integration of a closed nuclear fuel cycle is essential. As a leading contractor in that effort, we will continue to provide comprehensive support for the establishment of a closed nuclear fuel cycle.

To contribute to carbon neutrality and stable power supply in the future, we are promoting the development of an advanced light water reactor “SRZ-1200” that will ensure the world's highest level of safety. We are working toward achievement of commercialization in the mid-2030s which will see the introduction of a vast array of safety improvements that take into account innovative and proven technologies we have developed. To satisfy a diversified set of societal needs, we also intend to develop future reactors such as small light water reactors, high temperature gas-cooled reactors, fast reactors, and micro reactors. Furthermore, we will continue to support and perform additional research to support the development of fusion reactors, a permanent "dream energy source", from a long-term perspective after 2050.(**Figure 1**)

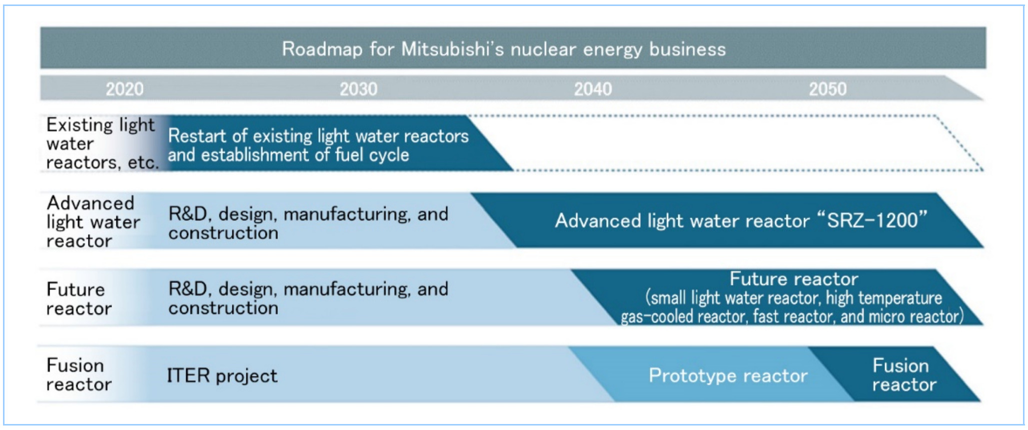


Figure 1 Our nuclear energy business's efforts to achieve carbon neutrality

3. Restart of existing light water reactors and establishment of fuel cycle

To achieve a nuclear power ratio of 20-22%, which is a prerequisite for reducing greenhouse gas emissions by 46% by 2030, many existing plants will need to be restarted.

In order to comply with the new regulatory requirements enacted after the Great East Japan Earthquake, we have made all-out efforts to support electric power companies in carrying out safety measures for existing plants in Japan and have successfully supported the restart of 10 PWR plants. We also achieved the restart of Mihama Unit 3 in June 2021, which was the first restart of a nuclear power plant in Japan that had been in operation for over 40 years. Regarding the installation of specialized safety facilities for existing PWR plants, as of August 2022, seven facilities have been completed. Even though we are not the manufacturer for Japan’s BWR plants, we have proactively been working with Japanese electric power companies to apply our lessons learned and knowhow to ensure a successful restart of these plants and further restore the public's confidence in nuclear energy.

For restarted plants, we will continuously conduct evaluations to ensure the proactive implementation of necessary safety improvements and implement maintenance measures that incorporate the latest knowledge and technologies. We also understand that we will have to systematically implement large-scale maintenance work, such as replacement of steam generators and reactor internals, to ensure we achieve long-term stable operation over a period of 60 years. These are just some of the efforts which will contribute to the safe and stable operation of nuclear power plants over a long period of time.

Reprocessing spent fuel from nuclear power plants and recycling recovered plutonium and other materials, to be used as MOX fuel, will enable, and ensure we effectively utilize uranium resources. Additionally, reprocessing will reduce the volume and radiotoxicity of high-level radioactive waste. As a leading contractor, we are promoting various types of work activities toward the early completion of the Reprocessing Plant and MOX Fuel Fabrication Plant that Japan Nuclear Fuel Limited is constructing in Rokkasho Village, Aomori Prefecture, to ultimately ensure the establishment of a closed nuclear fuel cycle.

4. Advanced light water reactor “SRZ-1200”

The SRZ-1200[*1] is a 1,200 MWe class advanced light water reactor with improved safety by incorporating innovative technologies and global lessons learned, all while ensuring high economic efficiency based on the culmination of proven technologies. The basic design has been proceeded in collaboration with four Japanese PWR utilities[*2].

The SRZ-1200 will achieve the world's highest level of safety conforming to Japan’s new regulatory requirements that incorporates lessons learned from Fukushima Daiichi accident. Development of the SRZ-1200 is in progress by taking advantage of the new construction that allows safety measures to be implemented from the design phase. In addition to strengthening its resistance to natural disasters, new safety mechanisms including passive equipment such as advanced accumulators and core catchers are introduced. Furthermore, a radioactive material release prevention system that will reduce the amount of radioactive material released in the event of a postulated accident is also introduced. (**Figure 2**)

*1 The name of SRZ-1200 has the following meaning:
S: Supreme safety, sustainability
R: Resilient light water reactor
Z: Ultimate type (Z) contributing to society with Zero Carbon emission
(In Japan, “Z” also has meaning of “ultimate type”)
1200: represents the electrical power output of 1,200MW

*2 Hokkaido Electric Power Co.,Inc., The Kansai Electric Power Co.,Inc., Shikoku Electric Power Co.,Inc., Kyushu Electric Power Co.,Inc.

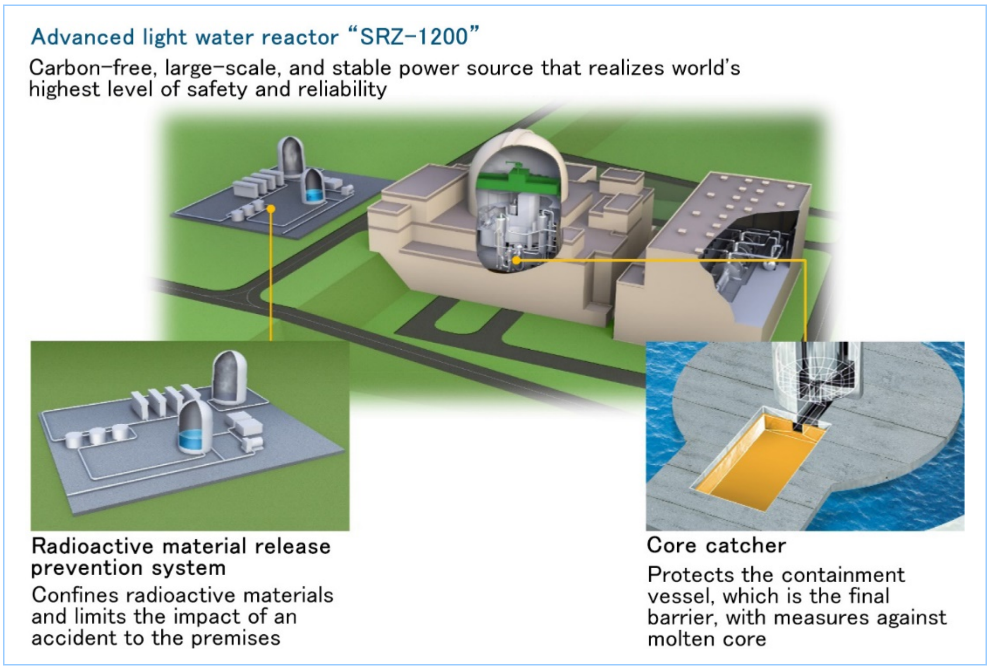


Figure 2 Advanced light water reactor “SRZ-1200”

The main features of the SRZ-1200 are as follows:

(1) Enhanced resistance to earthquakes, tsunamis, and other natural disasters

The seismic design includes sufficient margin for severe seismic conditions in Japan, including an enhanced seismic resistance by embedding the building in solid bedrock. The site ground level is so high not to be affected by tsunamis (dry site design). Resistance to other external disasters (typhoons, volcanoes, etc.) is significantly enhanced by making the building more robust and taking measures to prevent volcanic ash intrusion, etc.

(2) Enhanced core cooling and containment confinement

Achievement of core cooling and containment confinement is done through adoption of new safety designs, enhanced redundancy and diversity, etc., in compliance with the new regulatory requirements in Japan. These initiatives require both rapid response in the early stages of an accident and rapid accident restoration through the best mix of passive equipment that does not require a power source and operates automatically according to plant conditions (e.g., adoption of advanced accumulators) and active equipment that strongly demonstrates safety functions by being driven by a power source.

(3) Measures against core melt accident

Even in the unlikely event of a core melt (severe accident), the containment vessel, which is the final barrier preventing radioactive material release, is protected by capturing, cooling, and holding fuel debris in dedicated equipment area (core catcher).

(4) Prevention of radioactive material release

In addition to a filtered containment venting system, a radioactive material release prevention system that removes radioactive noble gases from the vent gas is introduced in the unlikely event that venting from the containment vessel is necessary to prevent a large release radioactive material, thus limiting the accident impact to the power plant site.

(5) Enhanced security (measure against terrorism)

APC (Airplane Crash) resistance was reinforced by adopting a double containment structure with a steel containment vessel and toughened external shielding walls, etc. Cyber security is enhanced with the integration of the latest DX technologies.

(6) Coexistence with renewable energy

Enhanced operational capability, for frequency control and load following, to mitigate typical issues such as output fluctuations during nighttime and stormy weather, along with power system instability associated with the expansion of renewable energy. In addition, the system can also be utilized for hydrogen production using generated surplus power.

5. Future reactor and fusion reactor

5.1 Small light water reactor

In recent years, small light water reactors (LWRs) have been attracting attention as a distributed power source for decarbonization. To meet the diversified needs of the future, MHI is developing a small LWR with an electrical output of about 300 MWe which is targeted to be commercialized around 2040 as a carbon-free power source for small-scale grids. Since the 2000s, MHI has been demonstrating elemental technologies specific to small LWRs through the development of the Integrated Modular Water Reactor (IMR). Additionally, we have been developing innovative small LWRs under the NEXIP (Nuclear Energy x Innovation Promotion) initiative of the Ministry of Economy, Trade and Industry (METI) from FY2019.

The small LWR adopts an integrated reactor structure in which the main components, such as the steam generator, are built into the reactor vessel, eliminating the need for primary coolant piping to connect the main components. It also naturally circulates primary coolant by using the density difference between the coolant heated in the core region in the reactor and the coolant cooled by the steam generator, eliminating the need for a main coolant pump. These features make it possible, in principle, to eliminate the postulated occurrence of accidents due to loss of coolant events resulting from the rupture of the primary coolant piping or due to a pump failure. For dealing with postulated accidents at the reactor, a passive safety system that requires no power source during an accident is actively adopted, eliminating the need for operation by an operator and for an external power/water source. In addition, the reactor and buildings containing safety equipment and other facilities are embedded underground to strengthen resistance to external hazards such as an airplane crash. Furthermore, even in the unlikely event of a major accident, the double containment structure enhances the confinement of radioactive materials. With the integration of these innovative concepts, we are continuously working toward the achievement of improvements in safety and reliability, when compared to conventional plants. (**Figure 3**)

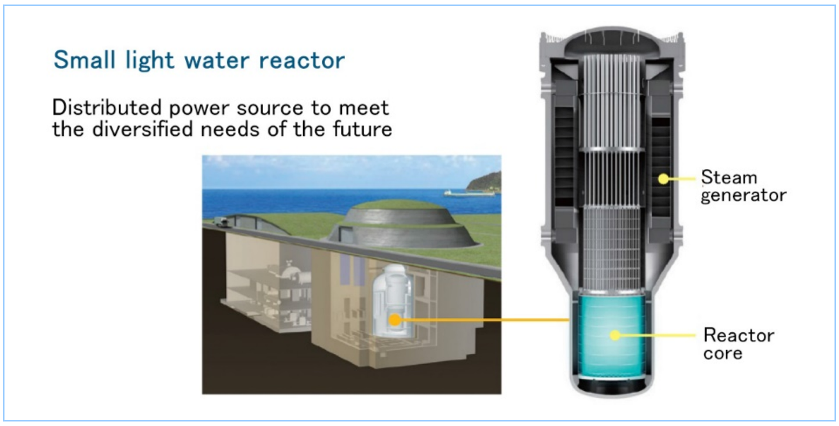


Figure 3 Small light water reactor

5.2 High temperature gas-cooled reactor

In addition to decarbonization in the power sector, decarbonization in the non-power sectors such as industry, commercial & residential, and transportation is essential for the achievement of carbon neutrality. In the steel and chemical sectors, hydrogen is used as a reductant and raw material. There are many technological developments underway for hydrogen utilization, along with carbon-free methods to generate hydrogen. In order to realize decarbonization of these sectors, a large and stable hydrogen supply is required.

A high temperature gas-cooled reactor (HTGR) is characterized by the utilization of nuclear heat at 900°C or higher and is capable of being used to generate large quantities of hydrogen for these sectors. A HTGR is characterized by the use of highly heat-resistant graphite (moderator) and SiC ceramics (fuel coating material) for the core and fuel, and the use of chemically stable helium gas as the coolant to extract nuclear heat. This approach allows the core heat to be naturally removed outside in the event of an accident. Therefore, in the event of an accident, the heat in the core can be naturally removed outside, and no core melt will occur.

We have been involved in the development of the HTGR since the 1970s and participated in the construction of the HTTR (High Temperature engineering Test Reactor) of the Japan Atomic Energy Agency (JAEA), which is the only HTGR in Japan, as the leading contractor. By utilizing our knowhow, we have been developing a plant system from 2019 that can produce several hundred thousand tons of hydrogen per year by using the high temperature heat source (950°C) from a HTGR with a maximum core output of 600 MWt under the NEXIP initiative of METI, aiming for commercialization around 2040. (**Figure 4**)

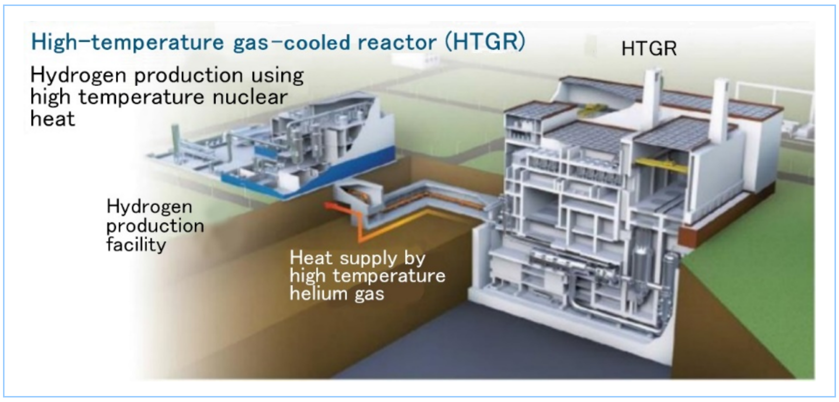


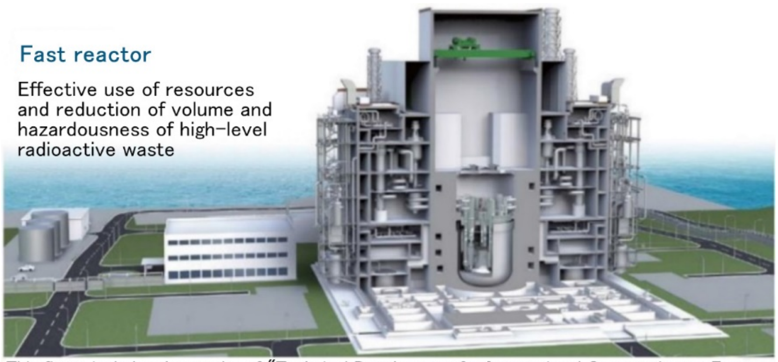
Figure 4 High temperature gas-cooled reactor (HTGR)

In April 2022, we have started a hydrogen production technology demonstration project utilizing a HTGR in collaboration with JAEA. We plan to connect a new hydrogen production facility (steam methane reforming method) to the existing HTTR and demonstrate this technology using the high temperature heat obtained from a HTGR. In collaboration with the National Institute of Advanced Industrial Science and Technology, we have also started to develop a high temperature steam electrolysis technology to produce hydrogen by efficiently electrolyzing steam using the ultra-high temperature nuclear heat of a HTGR as a carbon-free hydrogen production technology. By doing this and using a HTGR to generate hydrogen, we will first demonstrate hydrogen production using nuclear heat by applying steam methane reforming, which is at a high technological maturity level, for early commercialization. Then, in the future, we will demonstrate carbon-free hydrogen production technologies, such as high temperature steam electrolysis and methane pyrolysis, to ultimately realize large-scale and stable production of hydrogen.

5.3 Fast reactor

The fast reactor is a nuclear reactor that does not use water (moderator) to slow down neutrons but instead uses the fission reaction of plutonium by neutrons in a fast state. The fast reactor can also burn long-lived radioactive materials, called minor actinides (MA), which are recovered after fuel breeding and reprocessing of spent fuel from nuclear power plants. These MAs can be loaded as fuel again and converted into radioactive waste with short half-lives. Based on these characteristics of fast reactors, the Japanese government has set a policy to promote the development of fast reactors as part of its nuclear fuel cycle policy from the viewpoints of effective use of resources and ability to reduce the volume and radiotoxicity of high-level radioactive waste.

We have participated in national projects such as the development and construction of the experimental fast reactor "Joyo" and the prototype fast reactor "Monju" since the 1970s. In 2007, we were selected as a leading contractor for the development of fast reactors in Japan and since then we have been promoting the development of MOX-fueled sodium-cooled fast reactors, which is the most proven type of reactor. Under the NEXIP initiative of METI, we have also started the development of a compact sodium-cooled fast reactor with enhanced safety and reliability to expand the diversity of fast reactor applications. (**Figure 5**) For international cooperation promoted by the Japanese government, we have participated in the development of a tank-type fast reactor as a leading contractor of Japan's fast reactor development through international cooperation between Japan and France. In January 2022, we, together with JAEA, etc., agreed upon technological cooperation in the development of a demonstration reactor for a sodium-cooled fast reactor developed by TerraPower Technology Inc. of the United States. Aiming to start operation of the next-generation fast reactor at an early stage by the middle of the 21st century, we will contribute to the long-term stable supply of clean energy by developing a plant concept unique to Japan that takes into account the severe seismic conditions in Japan, utilizing knowledge we have obtained through international cooperation.



This figure includes the results of "Technical Development for International Cooperation on Fast Reactors, etc.", a project commissioned by METI.

Figure 5 Sodium-cooled fast reactor

5.4 Micro reactor

We are developing a multi-purpose modular-type micro reactor for use as a power source in remote islands, remote areas, micro-grids, etc., where power grids are not well developed. Micro reactors are portable reactors that are even smaller in power output level and size than small light water reactors and can contain the reactor core and power generation systems in a shipping container. This is accomplished by utilizing graphite-based materials, which have a lower density than metallic materials, for the core structure to reduce the reactor weight and downsizing the core. (**Figure 6**) Furthermore, to realize a long reactor core life that does not require frequent refueling, HALEU (High-Assy Low-Enriched Uranium) fuel with a maximum uranium enrichment of 20% will be used.

In pursuit of safety, the micro reactor adopts the concept of an "all-solid-state reactor" that uses high thermal conductivity materials instead of liquids or gases as a reactor coolant, thereby fundamentally eliminating the causes of postulated loss-of-coolant accidents and reducing the radiation impact on the environment. Even in the unlikely event of an accident, the reactor has low power output and uses graphite materials with high thermal conductivity, which allows for decay heat to be removed stably only by natural air cooling.

Figure 6 Micro reactor

5.5 Fusion Reactor

Fusion energy has the potential to contribute to solving the world's energy problems and be a solution to combat global warming. We are participating in the International Thermonuclear Experimental Reactor "ITER" project, which is being promoted through international cooperation among seven parties (Japan, Europe, the United States, Russia, China, South Korea, and India) by manufacturing major equipment which was developed from our advanced detailed design and manufacturing technologies. The ITER project is targeting achievement of the first plasma in 2025. In January 2020, we completed the first unit of the toroidal field coil, the world's largest superconducting coil, ahead of the rest of the world. (**Figure 7**) Other than the toroidal field coil, we have started fabrication of a divertor, which is an essential device for plasma confinement and discharge/removal of impurities.

We are also participating in the "Broader Approach" which is an international activity focused on the early realization of a prototype fusion reactor. This program is being carried out in parallel with the ITER project. The development of a prototype fusion reactor in Japan is proceeding according to the national roadmap. We are also working on the concept consideration of a plasma confinement vacuum vessel for the prototype reactor and the fabrication of components in equipment for a high-frequency heating system for the experimental fusion superconducting tokamak device "JT-60SA". These efforts are all based upon the application of design and manufacturing technologies we have cultivated over the years to support the fusion industry.

Going forward, we will continue to contribute to the realization of fusion energy by actively supporting the ITER project, which is leading an important effort in the development of technologies for global sustainability, and working on the prototype fusion reactor development program.

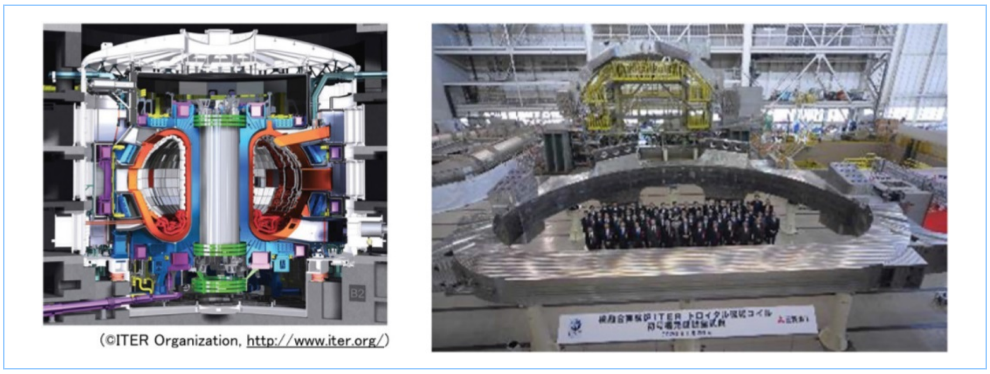


Figure 7 Unveiling ceremony of first unit of toroidal field coil for ITER

6. Conclusion

We are a comprehensive nuclear energy manufacturer involved in all areas of nuclear energy from light water reactors to fuel cycles, and decommissioning. Our company considers it a privilege to have contributed to the safe and stable operation of nuclear power plants for more than 50 years based on proven records and continuous innovation and remain committed to continue this achievement expectation for future generations.

Nuclear energy is a carbon-free, large-scale, and stable power source, and it will continue to be a critical power source for the future from the perspective of energy security in Japan, where natural resources are scarce. Nuclear power is the trump card for both future decarbonization and stable energy supply, and we will continue to contribute to the achievement of carbon neutrality by 2050 through application of our nuclear technologies.