

Several Considerations on Construction Site of Fusion DEMO^{*)}

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A fusion reactor is a human dream aiming to realize a terrestrial sun. The ITER project has been running for over ten years to create D-T burning plasma. Since a fusion DEMO design started within a framework of all-Japan system newly established in Japan, the construction site of the fusion DEMO must be investigated based on the discussions which have been performed for a long time in wide engineering fields. Some of the requirements to the site selection are discussed and summarized. The discussions are mainly focused on infrastructure which will be required to the construction site and very long timespan has been imaged from the construction to the site close after the D-T burning plasma operations. The plasma parameters and the in-vessel systems like the blanket and the diverter will not be discussed and the reactor type, such as Tokamak or Helical, is not concerned severely.

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1. Introduction

It is a human dream to realize a terrestrial sun and to get energy from it. To get reach to the terrestrial sun, the ITER project has been agreed as the first step of the international collaboration program in fusion. The ITER agreement was approved in 2007 and ten years have passed.

The global strategy to develop a fusion reactor in Japan has been discussed in the late of 1990s and the following story has been agreed that starts from the existing plasma devices, and continues the construction of the ITER, the fusion DEMO and finally development of a fusion commercial reactor as shown in Fig. 1. Almost same stories have been made by EU, USA, Russia, China, Korea and India which are participating countries in ITER project [1].

It was announced in 2015 that ITER first plasma would be created in 2025 which is the fastest schedule if everything goes on well and the additional budget should be approved by the participating countries. However, the budget has not been approved officially by Head of Delegation yet and it has not been opened how to assemble the cryostat, the toroidal field coils and the vacuum vessel in the engineering documents. Also, the strength of B2 slab (floor of the second level basement of ITER complex) seems not to have enough strength especially for assembling period of the components.

The JT-60SA [2] is under construction under the frame of Broader Approach program between Japan and EU. The JT-60SA will contribute not only to the ITER burning plasma operation but also to the fusion DEMO design. It is expected to create the first plasma in around 2020 and high

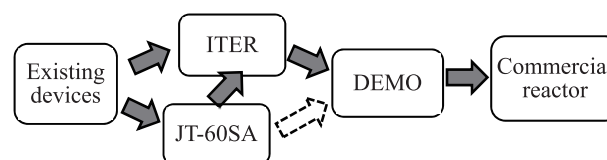


Fig. 1 Conceptual flow towards commercial fusion reactor.

beta plasma operations and diverter tests are anticipated.

Although the ITER project seems to be delayed more, the discussion on conceptual design of the fusion DEMO started in June in 2015 in Japan by establishing Joint Special Design Team at Rokkasho Institute of National Institute for Quantum and Radiological Science and Technology.

The fusion DEMO is assumed to be Tokamak in Japan because the Tokamak has been agreed as the first option for the fusion DEMO. The alternative magnetic confinement device is a Helical DEMO [3] of which design is undergoing at National Institute for Fusion Science. Since the ITER project seems to delay for more than several years, the Helical DEMO design would go on steadily to realize the continuous D-T burning plasma operation which is a common target of the Tokamak and the Helical DEMOs.

There are many common issues between the Tokamak and the Helical DEMO designs. The construction site selection is one of these common items. In this paper, the requirements for the construction site of the fusion DEMO will be discussed assuming some design parameters.

2. Requirements

The purpose of the fusion DEMO is to show the generation of electricity and the economic performance. The safety and the reliability of the operation systems are also to be verified. To confirm these contents, a lot of discus-

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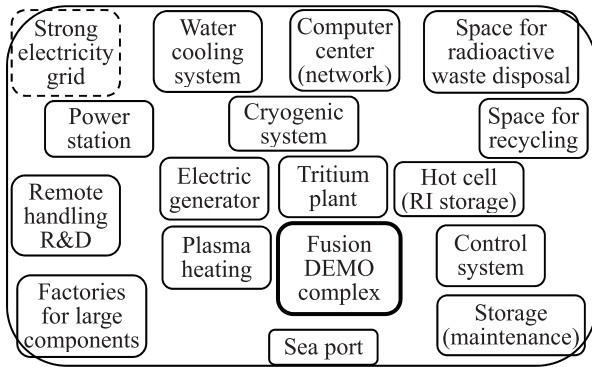


Fig. 2 Sketch of fusion DEMO construction site.

sions on the construction site of the fusion DEMO have been done.

A sketch of the construction site is shown in Fig. 2 which shows requirements for the construction site. The relative location of each system gives a conceptual image of the relationship to the DEMO complex. Among those items, the following items will be taken out as focused systems or spaces which must be taken in account when the construction site for the fusion DEMO is investigated.

2.1 Facility for remote handling R&D

The DEMO will generate and keep the D-T burning plasma continuously and provide the electricity. The 14 MeV neutrons will be created by the D-T reaction and the fusion energy will become available when the kinetic energy is changed to the thermal energy. To get the kinetic energy, the fast neutron must be captured by some atom. When the fast neutron is stopped by something, the kinetic energy transfers to the thermal energy. The atom which captures the fast neutron becomes the isotope for the additional neutron comes into the atom core. Some isotopes are radioactive, so the fast neutron activates the materials and components which covers the D-T burning plasma and the fusion DEMO will become radioactive. Some isotopes will emit gamma ray which damages organic materials.

The maintenance of the components and the equipment must be done periodically and correctly. The blanket and the diverter in the fusion DEMO must be replaced after a certain operation period. A lot of works, such as checking of sensors and cables, pipes and joints, cutting and welding, and so on must be performed in the radiation space. The remote handling system must be applied and functioned for the maintenance activity of the activated components, in the radiation environment, inside the bio-shield structure in the fusion DEMO complex, the hot cell, the tritium facility and the recycling facility. To develop and to confirm the reliability of the remote handling system, to certify the maintenance processes, the full scale mock-ups of the components and devices are needed.

Therefore, the buildings for the remote handling systems seem to be the same size or larger than the fusion DEMO complex, the hot cell and the tritium building.

2.2 Factories for large component

The fusion DEMO consists of huge-size components, such as the cryostat, the superconducting coils and the vacuum vessels. The diameter of the poloidal coils is supposed to be over 40 m and the height of the toroidal coils will be over 20 m. The weight of the TF coil will be around 1000 tons or more. It is very hard to transport these huge components from the company factories to the construction site by land because of the limitation of the land transportation. So, the manufacturing of these components will be carried out in the site ground or in the neighboring ground to the site. In another word, the onsite manufacturing must be carried out.

The onsite factories will not be permanent, but the factory buildings will be useful for the maintenance works and the storage of the parts. Since the lead blocks and concrete blocks for shielding are very heavy, the floor slab of the building must be strengthened.

When the site selection is performed, the space for these large buildings will be prepared and the utilization of the buildings after manufacturing works is to be considered.

2.3 Space for radioactive waste

As mentioned above, the 14 MeV neutrons will activate the materials surrounding the fusion DEMO. Therefore, the treatment and the management of the radioactive waste must be studied and discussed clearly considering the shutdown of the fusion DEMO and the site closing.

The fusion DEMO will excrete the low-level radioactive waste and no high-level waste because it does not have a uranium fuel pellet system like a fission reactor. One of the important rules on processing the radioactive waste is a clearance level defined in the Act for the Regulations of Nuclear Source Material, Nuclear Fuel Material and Reactors [4]. It lists the clearance level of each isotope and some data are as follows; ^3H ; < 100 Bq/g, ^{60}Co ; < 0.1 Bq/g, ^{54}Mn ; < 0.1 Bq/g. All the materials in the site will be checked and divided into several groups according to the radiation level and the materials (metals, non-metals, and so on). The materials possibly reused will be sent to the recycling process as discussed later.

The concrete of the fusion DEMO complex, the hot cell, the tritium building, and the recycling facility will be activated slightly by the neutrons streamed out of the vacuum vessel and secondary ones from isotopes. The total weight of the activated concrete will become large and the most possible process of these wastes will be "shallow grand disposal" in the site. The waste products lower than the clearance level will have potential to be processed as a general waste.

To perform such processing of the low-level radioactive waste, a wide space must be considered in the site or the neighboring ground when the site closing and the maintenance after the site closing is investigated.

2.4 Space for recycling facility

Some components of the fusion DEMO will be made of high quality metals such as Type 316 stainless steel and pure copper. These materials are equipped with mill sheets of the mechanical properties and the chemical compositions to guarantee very high performance and low impurities. The blanket will contain a lot of lithium and beryllium and the superconductors include much niobium and copper. These metals are activated but the recycling will be anticipated by a reason of a rare metal and the high quality. The metals will be re-melted and mixed with other used metals and new bars or new plates will be formed and brought out of the site after the radiation checking.

Regarding the non-metal materials, the concrete of the facility buildings, for example, will be crashed and mixed with the fresh concrete and will be used for the other applications. The organic materials such as the insulation materials will be oxidized to reduce the volume and the ashes will be compacted and solidified and processed according to the rules.

To sort and store the waste products, the wide space will be needed and the space for the recycling facility is also prepared. The scenario to process the radioactive waste products must be studied and established. The site selection will be done thinking of the investigations and the considerations on the radioactive products.

2.5 Strong electricity grid

The fusion DEMO will generate the electricity and much electricity is necessary to start up the device. Some investigations and calculations will be presented below assuming the design parameters.

2.5.1 Power supply for CS coil of tokamak DEMO

In case of Tokamak fusion DEMO, the CS coil will create the plasma current by shifting the poloidal magnetic field (Ohmic heating). The voltage of the CS coil between the coil leads (V_{cs}) is as follows:

$$V_{cs} = -L \times (dI_{cs}/dt), \quad (1)$$

where L is the inductance of the CS coil, I_{cs} is the current of the CS coil and t is time. When the CS coil has 5 H of the inductance and the coil current shifts from -50 kA to $+50$ kA in 60 seconds, V_{cs} becomes 8.4 kV. The electric power at the current of 50 kA will become 420 MW ($8.4 \text{ kV} \times 50 \text{ kA}$).

The insulation voltage of the coil is one of the key parameters in the magnet design. From the results of the ITER coil design activities, it is supposed that the maximum ground insulation voltage is 10 kV. When the maximum is less than 10 kV, the electric insulation technology has been established under the gamma ray dose of 10 MGy or the neutron fluence of $1.0 \times 10^{22} \text{ n/m}^2$. Therefore, the maximum power supply for the CS coil will be around 500 MW ($10 \text{ kV} \times 50 \text{ kA}$) in case of the maximum current of 50 kA. The above is a rough discussion and the detail

design of the power supply must be done correctly.

In case of the Helical DEMO, the required electric power will not become so large because the dI/dt of the coil could be controlled and kept on at smaller level.

2.5.2 Power supply for cooling water system

The electric power of the water cooling system is also concerned. When the blanket and the diverter systems are supposed to be water-cooled, the rough estimation on the electric power could be done as follows: The cooling water temperatures at the inlet and the outlet of the blankets are assumed to be 290 C and 320 C respectively, and the specific enthalpy of the saturated water is 1289.07 kJ/kg at 290 C and 1461.5 kJ/kg at 320 C taken from Steam Tables [5]. (Here, the effect of water pressure on the enthalpy is not considered.) When the heat load of 1.5 GW (1.4 GW is the fusion power and 0.1 GW is the plasma heating power) is assumed for the fusion DEMO, the water velocity could be calculated as follows:

$$Q = P_{\text{fus}} \times 60 / \Delta SE, \quad (2)$$

where Q is the water velocity in m^3/min , P_{fus} is the heat load of the fusion DEMO in kJ/s and ΔSE is the difference of specific enthalpy at 290 C and 320 C in kJ/kg. The water density is 1000 kg/m^3 . Under the above condition, the water velocity becomes about $522 \text{ m}^3/\text{min}$.

The water supplying power can be calculated by the following equation:

$$P = \rho \times Q \times H / (6.12 \times h), \quad (3)$$

where P is the electric power in kW, ρ is the specific gravity in 1000 kg/m^3 , Q is the water velocity in m^3/min , H is the pump head in m, and h is the pump efficiency. When the water velocity of $522 \text{ m}^3/\text{min}$ and the pump efficiency of 0.6 are applied, the electric power becomes 43.5 MW for the pressure difference of 3 MPa and 217.4 MW for 15 MPa of inlet pressure. From the results, it is noted that the power at the start-up of the system is around 200 MW for 1.5 GW heat load system and it is noted that the electric power becomes twice when the heat load is twice.

The cooling water circuit described above is the first circuit and it contains tritium because the water runs in the vacuum vessel and is irradiated by the fast neutron. So, there is the second cooling water circuit which connects to the first circuit with a large heat exchanger. The second circuit runs into the electric generator and comes back to the heat exchanger. The pressure drop of the second circuit will be smaller than the first one resulting in the smaller shaft power. If the pressure drop is assumed to be 5 MPa and the water velocity is $522 \text{ m}^3/\text{min}$, the power requirement under the above condition is about 72.5 MW.

2.5.3 Other facilities require high electric power

Another system which requires large electricity is the cryogenic system for helium liquefier and refrigeration. In case that the fusion DEMO needs 100 kW cryo-

genic system including the nuclear heating during the D-T burning plasma operation, the electric power of about 30.0 MW will be required assuming the helium refrigeration efficiency of 1/300. In addition, about 1.2 MW will be required for the cooling water system to take out the 30.0 MW from the cryogenic system under the condition of that the specific heat is 4.189 J/(gK), the temperature difference is 5 K and the pump head is 0.5 MPa.

The plasma heating devices also need large electricity. If the conversion efficiency is assumed to be 1/3 for both of ECH and NBI and the total input power to the burning plasma is 100.0 MW, the electric requirements becomes 300 MW. The 200.0 MW must be taken out by the cooling water and the shaft power will be about 8.0 MW under the same condition of the cryogenic system.

2.5.4 Strong request for secured grid

The electric power described in the above is summarized in Table 1. The power in the CS coil operation is supposed to be the maximum 500 MW because of the coil insulation voltage as described above. (The Helical DEMO will not request such huge electricity because of no CS coil system.) The supposed operation scenario is as follows: (1) the cryogenic system starts and then the cooling water system runs. (2) the coil system starts. (3) the D-T burning plasma is created and kept stably. (4) the shut down operation starts. Since there are many uncertainties in the power calculations and the only some components / systems are focused here, the figures in the Table 1 show the rough tendency of the energy consumption during the fusion DEMO operation.

When the water cooling and the superconducting coil systems start up, large energy will be needed in a short amount of time. Especially the start-up the CS coil operation requires huge energy in several tens of second. The plasma heating devices also need large electricity and it continues for a long time to generate the electricity. The energy conversion efficiency of the devices will be improved, but the degradation of the components has not been clarified fully, since the operation and the maintenance of the devices in the radiation environment have not been ex-

perienced practically. The integration of the experiments is needed.

As mentioned above, the Table 1 shows the performance of the electric power of the limited components / systems. But the total power will reach a few hundreds of MW which corresponds to the capacity of the normal middle-class electric power plant. Therefore, it must be carefully investigated and designed. When such huge electric power is consumed in a relatively short amount of time from the grid, the voltage of the grid would have a potential to come down. To prevent such sudden voltage-drop, the grid must be supported by enough power stations and strengthened against the quick voltage fluctuations. It should be noted that the fusion DEMO construction site would request the strongly secured electric grid.

3. Summary

The requirements for the site selection of the fusion DEMO have been discussed and several imperatives are studied under some conditions for the DEMO design. As illustrated in Fig. 2, there are key facilities to construct, to operate and to close the fusion DEMO. The safety is the highest priority and must be considered including the site closing.

Since the specification of the fusion DEMO is not clear, it is hard to design the facilities precisely, but it is valuable to investigate the facility design assuming the design targets. Also, it is meaningful to make an image of the integration of components. So, some considerations on the fusion DEMO construction site have been performed in this paper.

The remote handling R&D facility is very important to carry out the maintenance. The full-scale mock-ups will be required to establish the safe maintenance systems. Since some components are out of transportation size, the onsite manufacturing factories are necessary. These factories will be useful for the maintenance works and the storage after the operation starts. To process the radioactive waste in the site which shows the radiation over the clearance level, the wide space must be prepared. Also, the space for the facilities for reusing and recycling the materials used for the components of the fusion DEMO must be prepared. The practical design and the construction of these factories will be performed after the D-T burning operation under consideration of the materials processing. The fusion DEMO will need huge electric energy. Therefore, the strongly secured grid with high capacity is required.

Table 1 Summary of electric power described in the text. (Fusion power; 1.4 GW, Heating power; 0.1 GW) (MW).

	System Start-up	Magnet Operation	Burning Plasma	Shut down
CS coil power supply	0	ca 500	small	Energy recovered
Cooling water system	217.4	43.5	43.5+72.5	43.5+72.5
Cryogenic system	30.0+1.2	30.0+1.2	30.0+1.2	30.0+1.2
Plasma heating system	0.0	0.0	300.0+8.0	0.0
Total	248.6	574.7	455.2	147.2

- [1] ITER home page, <https://www.iter.org/>
- [2] JT-60SA home page, http://www-jt60.naka.qst.go.jp/jt60/html/mokuteki_jt60sa.html
- [3] NIFS home page, <http://www.nifs.ac.jp/>
- [4] The Act for the Regulations of Nuclear Source Material, Nuclear Fuel Material and Reactors, www.nsr.go.jp/data/000067232.pdf
- [5] Steam Tables, <https://www.steamtablesonline.com/>