Nuclear Fusion Technology (Tokamak) Safety Features for Thailand

Chantika Chinchatchawal [a*,b], Hokee KIM [a] , Wonho CHOE [a]
[a] *KINS-KAIST International Nuclear and Radiation Safety Program, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon, 34141, Korea*
[b] *Electricity Generating Authority of Thailand (EGAT),53 Moo 2 Charansanitwong Rd., Nonthaburi, Thailand, 11130*
[*] *Corresponding author: chantika.c@kaist.ac.kr*

1. Introduction

People have been seeking various new, clean, affordable, and reliable energy sources. One of the candidates of the future safe energy source is based on nuclear fusion. Nuclear fusion reaction occurs when two hydrogen isotopes are fused together. For instance, in the deuterium and tritium fusion reaction, an alpha particle and a neutron are produced as fusion products and the kinetic energy of the neutron is recovered and utilized for electricity production. Just like a conventional power plant, a fusion power plant will use this heat to produce steam and then electricity by way of turbines and generators. The tokamak is a type of magnetic plasma confinement devices being developed to harness the energy of fusion, and it is the leading candidate for a practical fusion reactor.

ITER (the Latin word for "The Way") is a large-scale scientific experiment intended to prove the viability of fusion as an energy source. ITER is currently under construction in the south of France. In an unprecedented international effort, seven partners—China, the European Union, India, Japan, Korea, Russia and the United States—have pooled their financial and scientific resources to build the biggest fusion reactor in history. ITER will not produce electricity, but it will resolve critical scientific and technical issues in order to take fusion to the point where industrial applications can be designed. By producing 500 MW of fusion power from 50 MW of power injected in the systems that heat the plasma—a "gain factor" of 10—ITER will open the way to the next step: a demonstration fusion power plant [1]. ITER will contain 840 m^3 plasma volume and its expected thermal power of 500 MW will be about 30 times more than the current world output record 16 MW from the Joint European Torus (JET) having 100 m^3 plasma volume achieved in 1997. ITER will be a prototype that can address many scientific and engineering issues before the Demonstration Fusion Power Plant (DEMO) reactors.

The main energy sources in Thailand are natural gas and coal [3], and therefore search for new energy sources to replace the existing fossil fuel based sources has been on-going. Nuclear fusion is certainly one of the candidates in this regard, and the study of tokamak technology and safety features will be useful for Thailand's electricity plan decision.

In this research, the first section will introduce the ITER tokamak basic operation. The second section will discuss the details of tokamak major components. Afterward, safety issues and safety features consideration of fusion reactors will be discussed. In the final section where interesting aspects of ITER and DEMO tokamak reactor safety and how they could adapt for Thailand's future electricity plan will be discussed.

2. Basic Operation

The ITER plant has two mains building (Fig.1); Tokamak Building (TB) and Hot Cell Complex (HCC) for support the operation, maintenance and decommissioning. The Hot Cell Complex consists of three areas, the Hot Cell Building (HCB), the Radwaste Building (RWB) and the Personnel Access Control Building (PACB) [5]. The fusion fuels (deuterium and tritium) are introduced from the Tritium Building to the reactor in Tokamak Building to generate fusion power.

The main fuel deuterium is extracted from seawater and tritium is produced from lithium reactions [6], [7]. These tritium and deuterium gases become ionized and heated to become an extremely hot plasma for fusion reactions to occur. To start the plasma, the first step is to remove air and other impurities from the vacuum vessel. Second, starting the magnet system, which is Toroidal and Poloidal magnetic field line to control the plasma and introduce the hydrogen isotope fuels to the vacuum vessel. Third, run the powerful electric current through the vessel, then gases will break down and ionized to become plasma [2]. These are a basic overview of the Tokamak operation and the next section will explain the details of five main parts of Tokamak: the vacuum vessel, magnets, blanket, divertor, and cryostat.

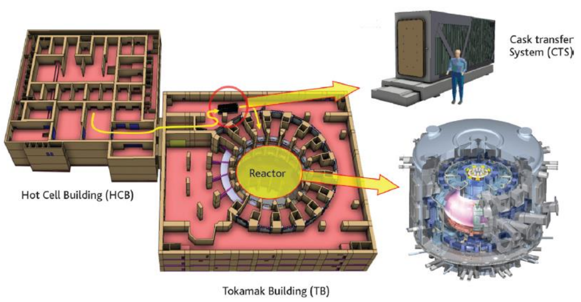

Fig.1. ITER Tokamak and Hot cell building [4]

3. Tokamak Major Components

There are mainly five parts in tokamak: vacuum vessel, magnets, blanket, divertor, and cryostat. Vacuum vessel and magnets are the core of fusion power reactor.

Blanket and divertor are plasma-facing components that directly face the heat load and plasma impurities [8]. The function of each component is briefly described.

3.1. Vacuum vessel (VV)

The D-shaped vacuum vessel is the heart of a fusion reactor (Fig. 2). Using to contain the extremely hot plasma that is about 100 million degrees Celsius and support other in-vessel components: blanket and divertor. In addition, high vacuum in the vacuum vessel provides the first barrier for plasma containment from the fusion reaction as radiation shielding.

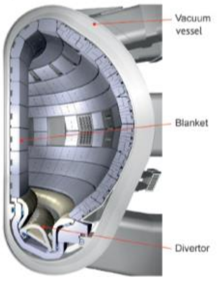

Fig. 2. Vacuum vessel and internal component [2]

3.2. Magnets

The magnet system contains toroidal field coils (TF), a central solenoid (CS), external poloidal field coils (PF), and correction coils (CC) [14] to shape, control and confine the plasma to create stability. The magnets will control the plasma particles to run roundly in the vacuum vessel without contacting the chamber wall during operation.

3.3. Blankets

Blanket modules cover the inner interior of the vacuum vessel wall to protect the wall from the hot plasmas as shielding components (Fig. 4). In addition, this part has to face the exact high temperature (plasma-facing component). Thus, selection of the material type is a necessary matter to focus on. Beryllium has chosen as the surface wall of blanket material because of low plasma contamination and low fuel detention property for safety issues. The rest parts of the blankets are built with copper and stainless steel [2].

3.4. Divertor

Divertor is cassette assemblies at the bottom of the vacuum chamber (Figs. 3,4). These highly loaded supporting structures mainly underlie exhaust or ash of helium gases from the fusion reaction. Moreover, divertor also contain diagnosis components for plasma control, optimization, and other physics assessment.

Fig.3 Divertor[2]

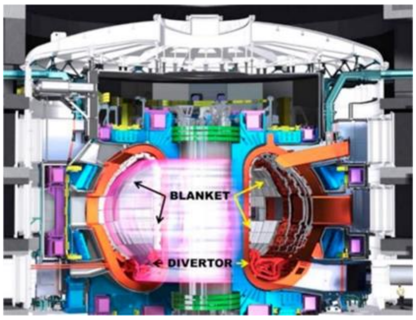

Fig.4 Location of the Blanket and Divertor in ITER [2]

3.5. Cryostat

The cryostat is a large stainless-steel outer layer that covers all the components in the vacuum chamber and magnets to ensure the high vacuum and extra-cooling environment in Tokamak. The cryostat has many penetrate channel for other supporting system and maintenance access (Fig.5). For examples, blanket removal for maintenance, cooling system connector and plasma diagnostics system.

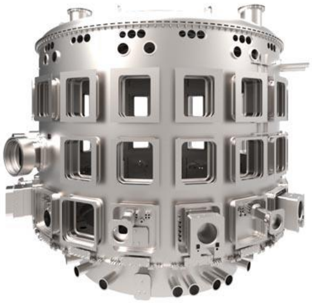

Fig.5 Cryostat [2]

4. Safety Issues and Safety Features

Every nuclear facility involved in ionizing radiation have followed the same two main safety objectives; confine the radioactive materials and limitation of ionizing radiation exposure to protect people and environment. For fusion reactions, tritium and neutron activation products are concerned. Defense-In-Depth and As Low As Reasonably Achievable (ALARA) are used to ensure safety concepts. The safety functions that define by ITER and also suitable for DEMO are Radioactivity confinement, Operational release control and Accidental release limitation. [12] In this section, five considerations of safety features for ITER and might relate to DEMO reactor are listed.

4.1 Decay heat removal

The removal of heat after shutting down the reactor might be the first safety concern of normal energy production system according to the past accident lesson learned. However, fusion reactor does not require a large number of radiation isotopes such as nuclear fuel as fission reactor and the major radiation sources are the reactor structure materials activated during the fusion process, producing a low level of residual heat in nature. In ITER it is not a safety requirement, loss of decay heat removal itself does not lead to any harmful result due to the certainly slow rise temperature that does not reach any material degradation. For example, the decay heat in ITER is low as around 11 MW at shutdown and fall to 0.6 MW within a day [4]. The current heat removal design uses a heat exchanger to transfer heat through the vacuum vessel cooling water loop. In the loss of power event, sufficient decay heat removal circulation is provided by a small pump run by the emergency diesel generators. If this cooling circuit complete fail, the studies have shown that outside atmosphere across the cryostat wall made the heat naturally radiated. [14] For future DEMO reactors that generate more power than ITER (500MW) the decay heat will be greater. Nonetheless, the advantages of using low-activation materials to minimize the risk of radiation exposure should also reduce the residual heat in the DEMO [4].

4.1.1 In-vessel LOCA

These issues will not be the problem for ITER but may consider in DEMO due to the higher level of decay heat removal. However, some loss of coolant accident (LOCA) analysis still has been carried out that passive safety function for DEMO heat removal is needed or not. [13]

4.2 Occupational Radiation Exposure

Even though the amount of radiation material is small than the fission reactor, the fusion by-products like tritium and the activated structure materials still require an occupational dose control. Fusion facility, similarly ITER or DEMO, an ALARA concept is required for minimizing radiation exposure. For example, by using remote handling (RH) tools in reaction areas during maintenance operations, workers cannot enter the Tokamak building during plasma operation, choosing low-activation materials in the plasma-facing component can minimize shutdown dose rates also provide capable shielding. Moreover, Maintenance procedures have to optimize to reduce the duration of human access to areas of high dose rate [12].

4.3 Environmental releases of tritium

Tritium from the fusion fuel cycle may leak from these possible events. For examples, from equipment in during normal operation and maintenance, from fuel storage in Hot Cell or while disposal await, from tritium recovery system that use to remove tritium from vacuum vessel's dust or solid elements before disposal and also from during the vacuum vessel maintenance. For ITER, these concern can be achieved by using the Heating Ventilation and Air-Conditioning (HVAC) systems to maintain sub-atmospheric pressure in Tritium and Tokamak building. When an abnormal condition occurs the Detritiation Systems (DS) will activate to collecting tritium that may release to the environment. [11,12] As for future DEMO plant, identify the system of tritium release levels and disposal path may need for a higher level of safety ensured.

4.4 Accidents

Postulated accident scenarios also one of important issue of safety. The selection of Accident sequences called "Reference Events" have provided in ITER's preliminary safety report. A Defense-in-Depth approach is taken to ensure that abnormal events are minimized by three concepts. [15]

- Redundancy: The safety system performs the same function equipment.
- Independency: designed system to be physically and electrically isolated from each other so that accidents in one series do not affect the other series.
- Failsafe principle: Appliances of safety system installations are designed to be in the safe direction when the control signals are lost, loss of power sources or loss of communication.

4.4.1 Fire and Hydrogen explosion

From the past nuclear accident lesson learned, the fire and Hydrogen explosion issues are one of the top accident consideration because it can lead to a severe accident. In ITER, two types of hydrogen actions are addressed. First is the risk of a hydrogen deflagration which can be flammable with air mixture. Second is the existed risk in Hot Cell which also the deflagration from recovered tritium from vacuum vessel's dust or components. The events mitigate plan by following systems such as fire detection and protection system, an air safety system that will control the concentrations within the limit, and designed building wall to prevent the overpressure. These similar precautions are taken in DEMO as well [12].

4.5 Radioactive Waste

Solid wastes in normal nuclear power plants are classified into high-level wastes such as spent nuclear fuel and other low and intermediate level wastes. Solid wastes in nuclear fusion reactors are major components such as plasma compositions and stainless steel can have classified into low and medium level wastes because they are not direct to high-level waste as spent fuel of nuclear power plants. The quantitative comparison of solid wastes and non-radioactivity in the nuclear fuel fusion reactor was confirm the safety of fusion power generation [16].

5. Conclusions

The ITER safety features have been issued as Engineering Design Activities (EDA) documents and the ITER plant design specification was issued by International Atomic Energy Agency (IAEA) in January 2002 [1]. However, for DEMO plant, additional safety features studies are still needed due to the characteristic differences of ITER and DEMO that are shown in Ref. [12]. To carry out the postulated plasma events and analysis that may occur, plasma diagnostics and fusion research are currently on-going.

Safety issues always a crucial topic for new energy technology and public acceptance. These considerations may lead the interest in nuclear fusion to Thai people. Besides, the study from ITER and DEMO fusion plant research from leading countries could be the guidance and gain plenty of knowledge for support Thailand's fusion energy decision shortly.

REFERENCES

[1] https://www.iter.org/faq#collapsible_3.

[2] ITER Organization 2019.

[3] EGAT, "EGAT Annual Report 2017," Thailand, 2017.

[4] IRSN, "Nuclear Fusion Reactors," *IRSN Rep. 2017/199*, no. November 17, p. 88, 2017.

[5] I. D. M. Uid, "Design Analysis for the development of the design of the ITER Hot Cell Complex (HHC)," pp. 0–11, 2016.

[6] D. K. Mansfield et al., "Enhancement of Tokamak Fusion Test Reactor performance by lithium conditioning," Phys. Plasmas, vol. 3, no. 5, pp. 1892–1897, 2002.

[7] A. Y. Chirkov and V. R. Vesnin, "Deuterium-lithium plasma as a source of fusion neutrons," J. Phys. Conf. Ser., vol. 891, no. 1, pp. 8–12, 2017.

[8] M. Merola et al., "ITER plasma-facing components," Fusion Eng. Des., vol. 85, no. 10–12, pp. 2312–2322, 2010.

[9] P. B. and Y. S. R Aymar1, "The ITER design," PLASMA Phys. Control. FUSION, vol. 1, pp. 1–30, 2002.

[10] M. Merola, F. Escourbiac, A. R. Raffray, P. Chappuis, T. Hirai, and S. Gicquel, "Engineering challenges and development of the ITER Blanket System and Divertor," Fusion Eng. Des., vol. 96–97, pp. 34–41, 2015.

[11] N. Taylor et. al., Preliminary safety analysis of ITER, Fusion Sci. Technol. 56 (2009) 573.

[12] N. Taylor and P. Cortes, "Lessons learnt from ITER safety & licensing for DEMO and future nuclear fusion facilities," *Fusion Eng. Des.*, vol. 89, no. 9–10, pp. 1995–2000, 2014.

[13] N. Taylor *et al.*, "Resolving safety issues for a demonstration fusion power plant," *Fusion Eng. Des.*, vol. 124, 2017.

[14] Taylor, N., Baker, D., Ciattaglia, S., Cortes, P., Elbez-uzan, J., Iseli, M., … Topilski, L. (2011). Updated safety analysis of ITER. Fusion Engineering and Design, 86(6–8), 619–622.

[15] Bou, M., C, F. R., Fourneron, J. M., Delong, J., Petitpas, P., & Campbell, D. (2016). Plant Control Design Handbook for Nuclear control systems. (ITER).

[16] NFRI, K-DEMO Conceptual Study Report, 2011