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Research and Technical Trend in Nuclear Fusion in Japan

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The energy shortage in near future has been a hot topic. Many countries and companies have introduced clean energy technologies such as solar, wind and water. In general, a large part of electricity comes from fire power plant. It is almost impossible to replace all of the fire plants into clean energy power plants since they cannot provide electricity stably. Nuclear fusion power has been considered as an ultimate solution for energy crisis and has been developed since the 1950s. Now it has come to the phase of practical power generation. A large construction of fusion reactor is in progress in France as an international cooperation. In this paper, we investigate Japan's R & D trend of nuclear fusion especially in tokamak reactor by making comparison with other countries to show future contribution to fusion society.

Keywords: nuclear fusion, energy diversity, magnetic confinement fusion.

1. Introduction

In 21th century, multi-polarity of the world economy arises such as BRICs (Brazil, Russia, India and China) or developing countries in Asia and Africa. Huge consumption of energy resources has been a critical issue to realize sustainable development under the conditions that not only for inhibiting the global warming but also constraining energy resources such as petroleum and water. As a solution of this state, 3E-vision has been discussed[1)]: Energy security, Environmental protection and Economic efficiency & sustainable economic growth. Those concepts enclose many aspects. For energy security, it stands for the shortage of energy, resources & food, the inequality in distribution and economic refugee. For environmental protection, it indicates the global warming, the destruction of forest, the destruction of ozone layer, marine pollution and acid rain. For economic efficiency & sustainable economic growth, it shows a contradiction that pursuing economic growth causes the destruction of environment or the disparity on the other side of earth. To solve this trilemma is extremely difficult and requires approach from the various fields. In Asian countries, which expected as the center of the future economic development, partnership between Japan and the ASEAN countries toward the realization of sustainable society has been established. This type of partnership or agreement have been established between many countries because the trilemma cannot be solved by one nation. International cooperation becomes much more important to push forward those problems in a strategic way.

In this paper, we focus on technological aspects to solve the expected energy crisis in near future. Specifically, it discusses the research and technical trend in nuclear fusion. First, technological aspects for energy issues are summarized and categorized to show differences between them. Second, the history and uniqueness of nuclear fusion are described. Then, the research and development trend in nuclear fusion is shown. Finally, results are summarized and discussion is given.

2. Technology for Energy Issue

Two third of electricity in the world comes from thermal power plant[2)]. It is well-known that the deposit of coal, petroleum and natural gas is finite and they are going to be depleted in near future. The amount of reserve and the estimated time for the depletion are controversial, however, the coming energy crisis is inevitable.

In recent days, so called "Renewable Energy" is getting attention and should be mentioned. The definition of renewable energy is broad, it means basically the energy resources that always exist and produce no greenhouse gas especially CO2. For example, solar power, wind power, water power, wave power, geothermal power and biomass are one of them. We do not go into detail on these technologies but let us summarize here. They are clean in terms of greenhouse gas and radioactive material production. Introduction of renewable energy power plant increases the energy self-sufficiency rate. It is beneficial for countries like Japan where energy resources are poor. However, the main problem for renewable energy is that the stable supply is difficult because many of them strongly depend on climate and seasons. Solar cell, for example, can only operate during sunny day-time to generate electricity. Water power can supply electricity constantly but possible locations are limited as it has to be close to mountain sides. For these limitations, it is not realistic to replace all of fire plant into renewable power plant. In Japan, nuclear power generation had been promoted until the tragic earthquake hit the east Japan in 2011. A huge tsunami destroyed nuclear power plant in Fukushima, causing melt-down and a massive release of radioactive substances. Japanese government had no choice but revises its policy of energy. The incident in Fukushima exposed the vulnerability in handling nuclear power plant even in one developed country Japan. In the present circumstances, Japan runs fire plants to complement the nuclear power plants.

3. Nuclear Fusion Energy

The nuclear fusion energy, which described in this paper, is quite different from the technology used in the current nuclear power plants. It should be noted briefly how it works to avoid misunderstandings. The principle used in general nuclear power plant is called nuclear fission. In fission power, we use Uranium 235. As a neutron hits Uranium, its nucleus separated into two nucleuses. When this reaction occurs there exists a difference in total mass between before and after the reaction. This difference of total mass is released as energy following the famous equation by Einstein ($E=mc^2$). The fission reaction also produces few neutrons and they hit other Uranium. By discreet controlling of reactions under the operational range enables a continuous production of energy. Fission requires careful control to prevent runaway of reactor and it is famous that tragedies happened in Chernobyl and Fukushima. In contrast, nuclear fusion uses light atoms such as deuterium and tritium (they are the isotopes of hydrogen). In the reaction between deuterium and tritium (D-T reaction), it produces helium atom and one neutral. There is also a mass difference before and after, which is equivalent to the energy released. The concept of fusion power plant is the utilization of this fusion reaction. The current state of fusion power plant is on the phase of practical generation of electricity. The theory of fusion is well-developed but there still remain a lot of technical issues to solve.

The uniqueness of nuclear fusion energy basically can be described as following[3]: (1) The deuterium as fuel exists 1cc within 3L of usual water. Therefore, there is no resource shortage for nuclear fusion. (2) It produces no waste that contaminates environment such as CO2 and there is no requirement of material treatment for ultra-long term. (3) The nuclear fusion reaction at the reactor core can be controlled safely. These three points are often mentioned when making a comparison with nuclear fission. Therefore, let us consider more in detail here. For (1), power generation output of 100 million kW with D-T reaction requires 200g of deuterium per day. 150 ppm of hydrogen isotope within whole amount of water in the ocean is deuterium, therefore we can say deuterium deposit is inexhaustible. The question is how to separate it from water practically. There is a misunderstanding that the separation of water by electrolysis takes huge amount of energy and this makes fusion impossible to generate net of energy at all. It is true that to divide water by electrolysis and proceed isotope separation consume great deal of energy, however, water molecular itself has a slight difference in chemical property whether it contains normal hydrogen or deuterium. Making use of this difference, it is possible to separate deuterium efficiently. Plants for the deuterium separation already exist all over the world. Especially, in Canada, it has been well-developed and commercialized. For (2), one should mention that radioactive materials can be produced during the operation of fusion reactor. Tritium as fuel is radioactive and it is difficult to produce in terms of cost. Therefore, it can be produced by nuclear reactions between lithium and neutrals from fusion reaction inside the blanket. The blanket is a device located inside of fusion reactor that contains lithium to produce tritium and inject it as fuel into fusion plasma. The point is that only few percent of the injected fuels (deuterium and tritium) can make fusion reaction so that the rest would be released as exhaust emission. Tritium has mobility and it must be carefully handled. Another radioactive material can be also produced that energetic neutrals from fusion plasma make plasma facing components radioactive. This kind of radioactive is solid state and low level that it is relatively easy to handle compared with radioactive from fission power reactor. Technology for the blanket has been a key issue and intensively studied. Finally, about (3), we see the reason why there is no runaway with fusion reactor. In magnetic confinement of fusion plasma, the possible operation range for fusion reaction is very narrow. Such required temperature and density of plasma are sensitive for fuel injection or impurities. If there is an error in operation such as excess supply of fuel, it cannot sustain the reaction conditions. Then, it terminates automatically. Of course, a sudden termination can cause a damage to the reactor so that safe operation is also of importance. In these manner, nuclear fusion energy is not perfectly clean. Even though, the amount of energy that it can produce would be enormous. As one alternative, nuclear fusion should be taken account.

What makes fusion so difficult? It will be also mentioned in next section that for fusion reaction both high performance plasma and high confinement of plasma are required. These conditions are against each other, such high-performance plasma with high temperature and density tries to escape from confinement area. For this purpose, a large construction of fusion device is needed to sustain fusion reaction by applying large amplitude of magnetic field. Note that for D-T reaction, temperature more than 100 million Celsius is necessary. Not only for making fusion reaction, we also need to consider: electricity generation system, materials with heat-resistance, fuel recycling, safety operation and so on.

There are mainly 11 technical considerations for realizing a fusion tokamak reactor: superconducting coils, blanket, divertor, plasma heating & current drive, physics & simulation, core plasma physics, fusion fuel system, materials of reactor, reactor safety design, occupancy rate & maintainability and measurement & control[4]. Here, brief explanations for some terminologies are given. First, superconducting coil is a specialized coil that can produce strong magnetic field. The superconducting condition makes metal materials no electrical resistance that high current can generate much higher magnetic field. For this condition, extreme cooling of coil is necessary. Therefore, separation between hot plasma and superconducting coils are to be realized. This poses technical difficulties and a large complex construction is indispensable. Second, divertor is a part of tokamak that exhaust helium or impurities from reaction to sustain long-duration tokamak operation. It is also the area where the strongest heat load comes due to magnetic field configuration. Since the expected heat load in fusion reactor would be 10 MW per m^{-2}, which is an order of magnitude larger than fission reactor. Maintainability of reactor should be also mentioned. In a fusion power plant, materials and equipment inside the reactor are to be radioactivated by energetic neutrals from fusion reaction. Maintenance by human will be impossible so that remote maintenance by machines are planned.

3.1 History of Fusion Research and Development

The stream of fusion energy research started from late 1920s. R. Atkinson and F. G. Houtermans suggested that the energy source of stars is some sort of nuclear reactions [5]. The quantitative evaluation of nuclear fusion were first revealed in late 1930s. After this discovery, research and development toward nuclear fusion power, which would be the ultimate solution for energy crisis, has been carried out since the 1940s. An important note on 1950 is that a famous astronomical scientist L. Spitzer at Princeton University first came up with the idea of "stellarator", which confines hot plasma by applied twisted magnetic field[6]. First, fusion research was classified in the US during the cold war, but at 2nd UN Atoms for Peace Conference in 1958, it was declassified because researcher in the US and others found the realization of fusion was much difficult than expected[7]. As a consequence, research and development in fusion has initiated based on international cooperation since then. In the 1960s, fusion research suffered its poor confinement of plasma. However, things changed when Tokamak T-3 at the Kurchatov Institute reached 1keV (more than 10 million degrees) electron temperature which is much greater than the stellarator in 1968[8]. Tokamak is another type of plasma confinement, which twists magnetic field by producing current inside of plasma. This success made tokamak device a main trend in fusion research and development. This trend has continued until now. The plasma confinement and its temperature have improved. Then, in the 1980s, large constructions of tokamak had begun such as JT-60 (Japan), TFTR (US) and JET (EU). As for stellarator (also called as Helical device), it also had started constructions of large devices such as LHD (Japan) in the 1990s. As another technology for fusion power, inertial confinement fusion has to be described. Inertial confinement is different from magnetic confinement as tokamak or helical devices. To make fusion reaction, it uses ultra-high-power laser to compress and heat up fuel at the condition where fusion reaction is possible. In this paper, although we are not going through the helical device and inertial fusion device, recent development for laser fusion has been also significant.

ITER (International Thermonuclear Experimental Reactor) project is now in progress. ITER will be the first fusion device to produce net energy. And ITER will be the first fusion device to test the integrated technologies, materials, and physics regimes necessary for the commercial production of fusion-based electricity[9]. Thousands of engineers and scientists have contributed to the design of ITER since the idea for an international joint experiment in fusion was first launched in 1985. The ITER Members—China, the European Union, India, Japan, Korea, Russia and the United States—are now engaged in a 35-year collaboration to build and operate the ITER experimental device, and together bring fusion to the point where a demonstration fusion reactor can be designed. It is now under construction in southern France and will start operation around 2025. The main targets of ITER specified to: (1) Produce 500 MW of fusion power, (2) Demonstrate the integrated operation of technologies for a fusion power plant, (3) Achieve a deuterium-tritium plasma in which the reaction is sustained through internal heating, (4) Tritium test breeding and (5) Demonstrate the safety characteristics of a fusion device. The ITER reactor will have diameter of 30m and height of 25m (see Fig. 1). This size is much larger than a conventional fission reactor and any other fusion tokamak device that has been built ever. Therefore, the construction itself is a challenging task. ITER will test the feasibility of fusion power plant. Japan as a member of ITER has been a leading country in technological aspects. Many parts and methods for ITER have been designed and manufacturing by institutes and companies in Japan.

4. Nuclear Fusion Trend in Japan

Fusion energy trend in Japan will be presented. In the priority plan of government, there are 4 fields in nuclear fusion development: (1) Tokamak plan, (2) LHD (Large Helical Device) plan (3) Laser scheme fusion (4) Furnace engineering[10]. Although tokamak is the most developed technology, other method of fusion energy is necessary to expand the diversity and alternatives. Especially in helical device, we have a large experimental device called LHD in Toki, Gifu prefecture. Its technique how to confine plasma is similar to tokamak configuration, in terms of making use of magnetic field. Then, research and technology interactions between them are actively

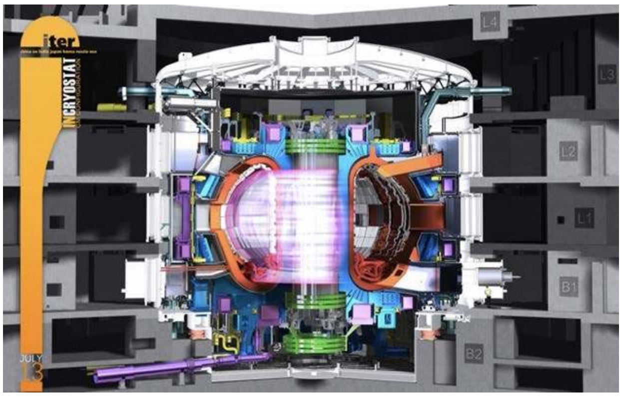
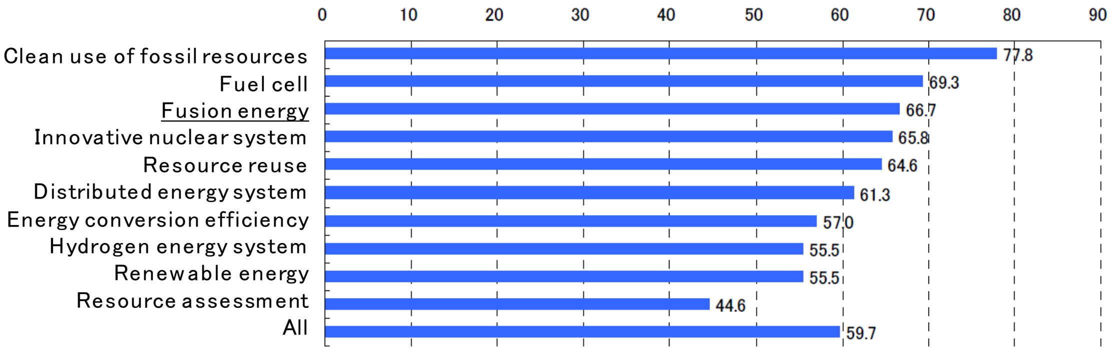


Fig. 1. ITER Tokamak Design[9]

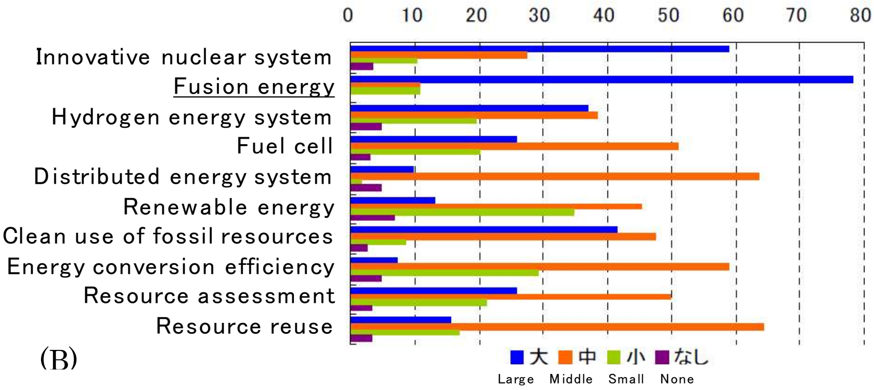
conducted. Furnace engineering is also important from the viewpoint of fundamental research. As one country, to design a prototype reactor is highly important because one must have its own design of nuclear fusion reactor. Based on the knowledge and technology for ITER, Japan has started its own prototype reactor designing.

Fusion energy is one of energy policy in Japan. The importance of energy policy has been intensively discussed year by year. There are several fields in Japanese energy policy, for example, fuel cell, hydrogen energy and renewable energy. The importance index by technological sectors in Japan is shown in Fig. 2 (A)[11]. Fusion energy is an important issue in the third. The notable difference between fusion energy and other energy resources is that fusion power is not still available. In another word, government assistance is necessary for the further development. In some fields such as renewable energy or fuel cell, private companies have already entered into whole system production. However, nuclear fusion power has not been commercialized. In Fig. 2 (B)[11], the need for government involvement in different fields is shown. For fusion energy, it shows that the Japan government considers its involvement in this field is indispensable.

Nuclear fusion is regarded as one important issue on energy policy in Japan. The next question is how much budget is practically spent on the research and development of nuclear fusion. Figure 3 illustrates the itinerancy of national budget on fusion sector from 1971 to 2007[12]. The amount of budget has been decreasing since 1997. One of the reasons of decreasing budget is clearly the stall of the Japanese economy. Another reason is that a large construction of LHD at Toki finished around 1998. Therefore, the budget after the construction has been used mainly for the running cost of those huge equipment. Along with the reduction of budget, working population in this field has been also decreasing. According to a report by Japan Atomic Industrial Forum[12], it says that R & D of fusion energy has been supported only by the government, therefore, it highly depends on national budget from the viewpoint of the market. Earnings of companies in this field basically keep decreasing. It also mentions that since the developments of large experimental devices are always single orders and long-term, inheritance of technology should be difficult. Development such fusion energy has to be a long-term national project, however, companies have to take risks to



(A)



(B)

Fig. 2. A) The importance index by technological sectors in Japan[11], B) The need for government involvement in energy policy in Japan[11]

the participation or cooperation. From the industry side, to prepare for the ITER construction and BA plan, it presented three issues. (1) The current number of technicians and equipment of industry cannot cover the requirements so that government approach and scenario must be valid. (2) Inheritance of technology is essential. The training of the next generation is in the urgent need. (3) Availability and procurement of materials for long-duration should be considered.

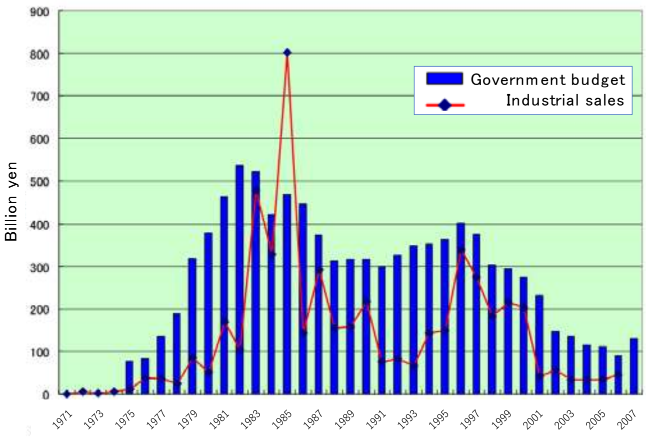


Fig. 3. Government budget for nuclear fusion energy[12)]

Let us see another trend in fusion community in Japan. Nuclear fusion forum has established in 2007 in Japan. Its purpose is to enhance research and development activities between university, research institute and industry toward the realization of nuclear fusion. Figure 4 is the composition ratio by affiliation of members that constitute the forum[13)]. As it shows, about 40 % of member comes from university, furthermore, NIFS (National Institute for Fusion Science) and JAEA (Japan Atomic Energy Agency) are the institutes under the government. That is, 75 % of member comes from public organizations. It cannot say that it reflects the general structure of nuclear fusion cluster, however, we can estimate that the general understating and recognition are very low even though a huge amount of budget has been introduced.

Research and development level of Japan in energy related area against US are shown in Fig. 5[11)]. Note that the data was collected in 2000s therefore it cannot describe current state. However, it shows our interests in clean energy, where energy resource is poor and dependence on foreign supplier is large.

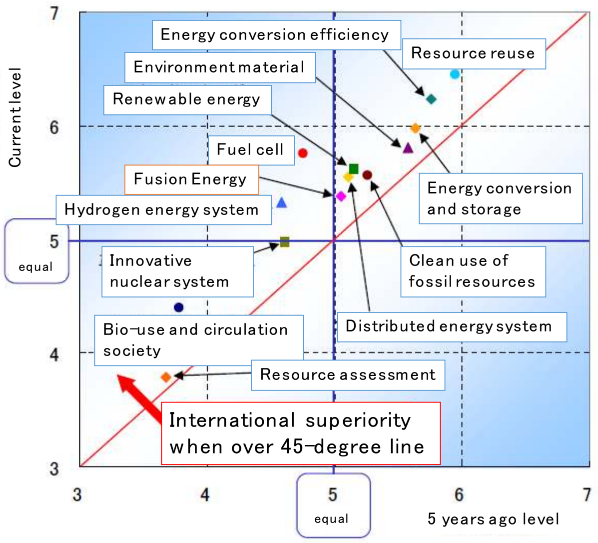


Fig. 5. Research and development level of Japan in energy related area against US[11)]

By utilizing google scholar, we can see how much scientific papers or related documents published during a specific term. Mainly five fields in which research activities in tokamak development are chosen: divertor, plasma simulation, operation system, current drive of plasma and plasma facing materials. The result includes published documents from all over the world. Therefore, to investigate Japan's trend needs another method but it is convenient to take a brief look at overall picture. As it is denoted in Fig. 6, search hits on plasma facing materials (PFM) rapidly increased. This can be understood that PMF is now the hottest topic for magnetic confinement of fusion. Compared with other fields, the question what kind of material or method should be used for PFM to endure the harsh environment is not yet valid. In addition, PFM can be studied without large equipment and

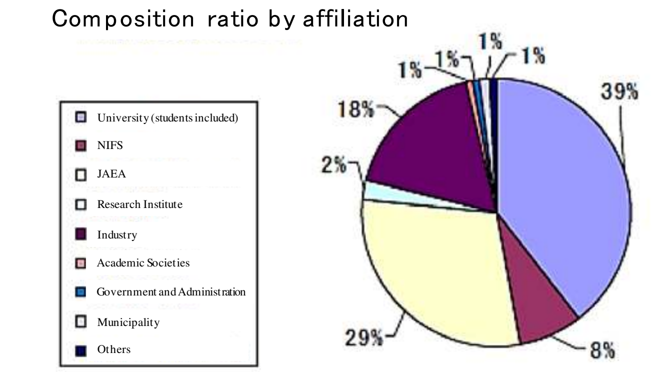


Fig. 4. The composition ration by affiliation of fusion energy forum[13)]

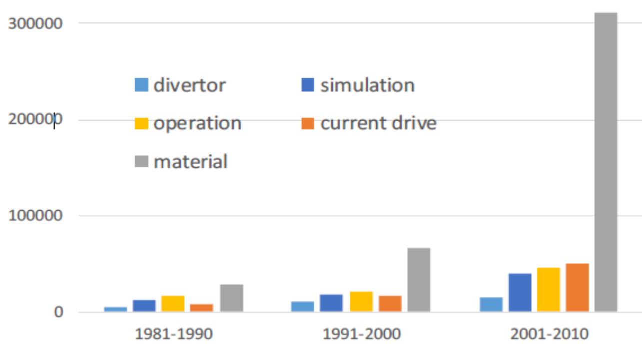


Fig. 6. Search hits on Google scholar with specific research field of nuclear fusion

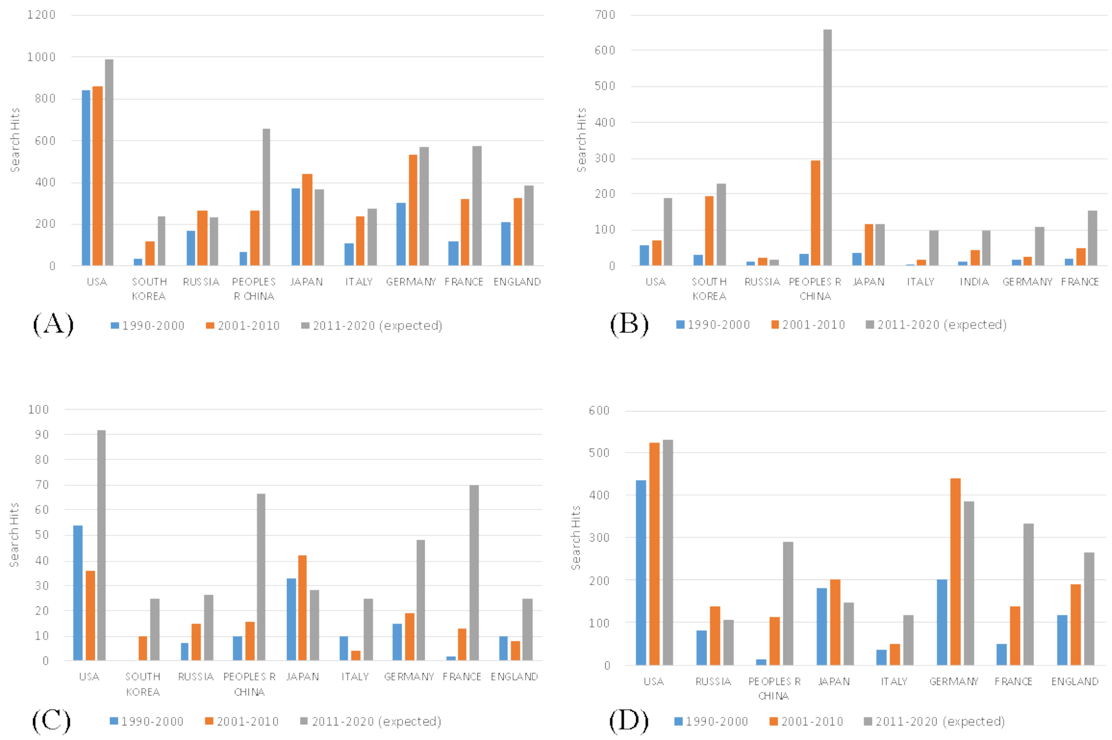


Fig. 7. R & D Trend in technical fields: A) Heating, B) Superconducting Coils, C) Blanket and D) Divertor

relatively easy to conduct experiments with small device. Even though the budget and working population on nuclear fusion are in decrease in Japan, it shows research activities on international scale has been intensively promoted toward the construction of ITER and the commercialization of nuclear fusion power plant[14].

To investigate Japan's fusion R & D trend, an analysis on Web of Science has been conducted. The method is similar to the Google scholar search but Web of Science can provide specific information. It can search scientific paper by published time, region (countries), fields and institutions. To evaluate the trend in Japan and to make comparisons with other counties, major fusion topics are selected: heating, superconducting coils, blanket and divertor. These keywords were chosen to search hits combined with a keyword of Tokamak by a specific duration of publication. Figure 7 shows the results of search by making comparisons with major countries. Note that the values of term 2011 to 2020 are calculated by a simple assumption that the number of publication would be the same with the average number per year during 2011 to 2016. In every field, the amount of publication in Japan is supposed to degrease in the third term up until 2020. Currently in Japan, only small or middle class of tokamak are in operation and now large superconducting tokamak called JT-60SA is under construction. Since it will start operation around 2020, the number would increase hopefully after the first plasma operation of JT-60SA. Compared with other countries, Japan has been leading and constantly contributed to fusion R & D. However, in recent years, the number is getting smaller. In contrast, advancement of China has been remarkable. In the selected four fields, the expected growth rate of China would be much higher than other countries. Large tokamaks have been operating in China these days, showing the sense of energy crisis accompanied with increasing population and domestic energy demand. South Korea has a large tokamak device KSTAR, R & D activities in South Korea are also notable. ITER is located in France, therefore, the EU countries have contributed to the fusion society constantly. In the US, they have a large tokamak DIII-D in San Jose, a middle-sized advanced tokamak NSTX-U in Princeton and several small to middle tokamaks. Researchers in US frequently have conduct collaborative research with other countries. For these reasons, US has been a leading country in fusion R & D.

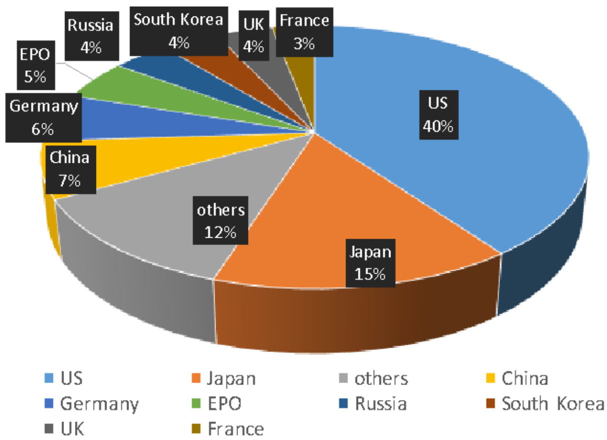


Fig. 8. Geographical Distribution of IP in Nuclear Fusion Technology[15]. *EPO (European Patent Office)

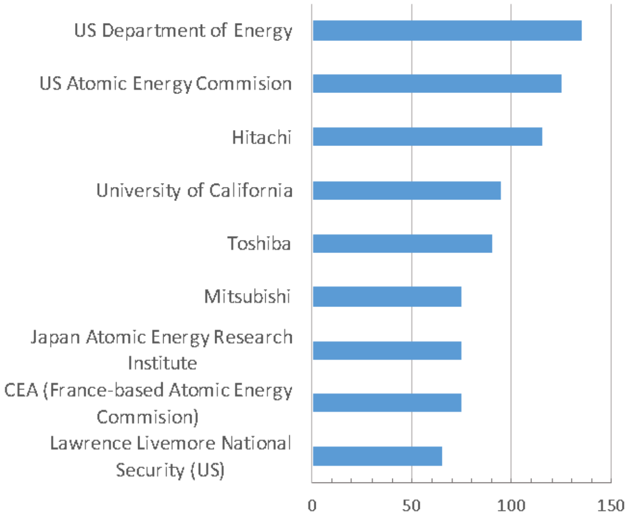


Fig. 9. Leading Owners of Nuclear Fusion Patent Portfolios in the World[15)]

In addition to published papers, it is also of interest to investigate intellectual property (IP) assets, which include patent applications and granted patents. IP assets can be a measure of its commercialization or technological development, on the other hand, published paper refers to the progress of scientific research mostly. The following results have been presented on a report by iRunaway[15)]. In Fig. 8, it shows a geographical distribution of IP in terms of countries. We can see the same trend with fig. 7 that the US holds the largest number of IP assets. Japan follows in the second place. Note that the data in Fig. 8 includes not only magnetic type of confinement but also other types such as inertial confinements, represented by laser fusion technology. In the graph, the EU countries are separately illustrated so that contributions as EU have an impact than Japan.

Next, we look into the recent trend in IP assets along the time series (1990 to 2014) in Fig. 9. Each circle mentioning the number of patents for the assignee. It shows good agreement with the previously mentioned trend in Fig. 7 that the US, Japan and EU nations have been leading the development of fusion technology. Also, China had become influential around 2008 and took the first place in number of assets in 2014. This remarkable rise of China is also in accord with the rise of publications in Fig. 7. We have seen the distribution of IPs in the world and time series in recent years. The report by iRunway also represents interesting data of IP owners. In Fig. 9, it shows the distribution of patent owners as organizations or companies. Here, CEA is France-based atomic energy commission, which operates ITER project. It is notable that owners are government organizations or universities in the US, however, companies such as Hitachi and Toshiba hold patents in the large scale. The reason of this difference is not yet clear and this would be one of future works.

5. Conceptual Reactor Design

We have discussed the trend of fusion technology, focusing on tokamak type of plasma confinement of plasma. Besides, there is a wide range of design approaches: tokamak, stellarator, spherical tokamak (ST), reversed-field pinch (RFP), spheromak, field-reversed configuration (FRC) and tandem mirror (TM). Since 1960s to present, 50 conceptual power plant design studies have been conducted worldwide[16)]. In ref. 16, detailed explanations are denoted. We do not focus to investigate the differences of those types of magnetic confinement. Therefore, in Fig. 10, the timeline of conceptual power plant designs is presented. Tokamak type has been frequently developed as a whole. However, after 1980, it had started designing other types of reactor for 10 years and then shifted to tokamak again. This process shows that tokamak type has been elected as the most promising for fusion reactor. When we look into recent concepts of reactor, we can find a trend that compactness has become important. Compactness can directly contribute to the cost-effectiveness since larger device gives rise of construction cost.

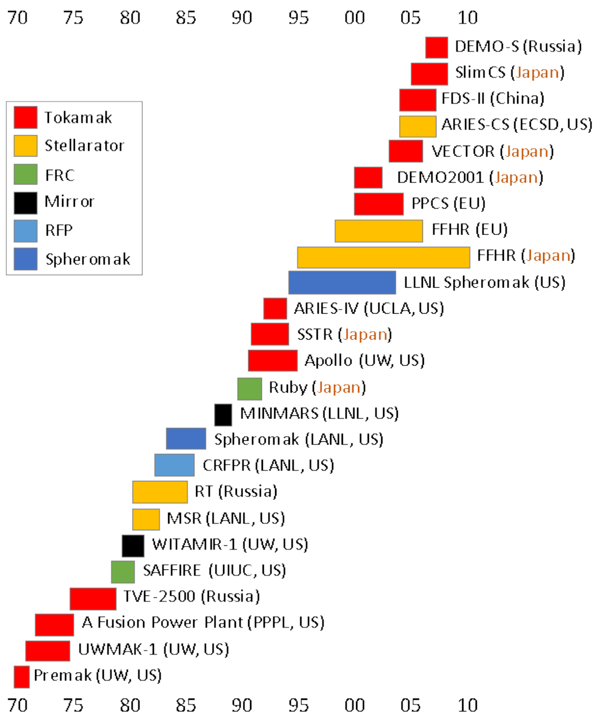


Fig. 10. Timeline of large-scale conceptual power plant designs developed worldwide for magnetic fusion[16)].

6. Summary and Discussion

Research and development trend in tokamak fusion energy has been investigated in this paper. Toward ITER project, R & D activities have been intensively conducted mainly by ITER members. As for Japan, the government regards fusion energy as one important energy policy. Since it is not yet commercialized, official intervention is strongly in need to support its development. We also see that the amount of budget for fusion in Japan has been decreasing in these years, because of economic slowdown and the completion of large devices. R & D activities in nuclear fusion greatly depend on progress in large device experiments. This trend poses some problems that huge constructions cannot train new technician and researcher or provide opportunities for companies that they are not continuous. In addition to published papers, the trend in IP assets has been discussed. The results are in accord with the trend in published paper. It is notable that companies hold IP assets in Japan but public institutions hold them in the US. On a global scale, R & D activities for fusion energy has evolved toward ITER. Especially, the recent advancements in China and South Korea have been remarkable. As for Japan, activities in fusion have been slumping these days. However, we can expect contribution of Japan will increase in five years after the initiation of JT-60SA based on historical point of view. As a measure of fusion trend, we included the trend in conceptual designs. These designs have not been constructed practically, however, it is important to assure the feasibility of fusion reactor. The design trend shows tokamak has become a primary method and compactness of reactor has been getting attention toward commercialization. International R & D toward fusion power has steadily progressed until now. To take a leadership in nuclear fusion internationally, Japan has to solve problems in talent shortage by enhancing the understanding of general and opportunities for company participation.

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