Environmental and economical assessment of various fusion reactors by the calculation of CO₂ emission amount

S. Uemura, K. Yamazaki, H. Arimoto, T. Oishi, T. Shoji
Department of Energy Engineering and Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 466-8603, Japan

We compared several fusion reactors from the view point of CO₂ emission amount. Magnetic confinement systems we evaluated are Tokamak Reactor (TR), Helical Reactor (HR) and Spherical Tokamak reactor (ST). These models are calculated by Physics Engineering Cost (PEC) code. Parameters of Inertial confinement fusion Reactor (IR) is simply calculated by given pellet gains. In addition, different blanket modules and fuels are considered in TR designs. To calculate CO₂ emission amount of fusion reactor defined by plasma parameters and radial build, we used basic unit for CO₂ weights (k-t-CO₂/t-material). Calculation results indicate that CO₂ is the most emitted from the construction stage of coil systems for magnetic confinement fusion reactors. For the IR design, the construction stage of driver system and pellet purification stages involve much CO₂ emission. By comparing fusion reactors with other power generation systems from the view point of CO₂ emission amount, we confirmed that fusion reactor emits less CO₂. Therefore, there is little influence on economics of fusion reactors by introducing carbon tax.

Keywords: Tokamak Reactor (TR), Helical Reactor (HR), Spherical Tokamak reactor (ST), Inertial confinement fusion Reactor (IR), blanket, CO₂ emission amount, Cost Of Electricity (COE)

1. Introduction
Fusion reactor is expected to be one of abundant energy resources in the future. However there are many technological problems to be solved. In addition it is essential to assess safety, economics and environmental burden of fusion reactor. In this paper we calculated the Cost Of Electricity (COE) and CO₂ emission amount for several types of fusion reactors. And to assess economics and environmental issues at once, we considered the case of introduction of carbon tax.

2. Assessment procedure
Confinement systems we evaluated here are three types of magnetic confinement fusion reactors (Tokamak Reactor (TR), Helical Reactor (HR) and Spherical Tokamak reactor (ST)) and Inertial confinement fusion Reactor (IR). Several blanket modules and fuel systems (D-T or D-3He) are considered in TR. We used Physics Engineering Cost code (PEC code) [1, 2] to calculate COE of magnetic confinement fusion reactors. PEC code is a code which calculates plasma parameters and radial build of fusion reactor with input parameters such as net electric power output and ignition margin.

The calculation flow of IR parameter is shown in Fig.1. Driver systems quoted here are Kr-F laser of SIRIUS-P [3] (driver energy is 3.4 MJ with 7.5% efficiency) and heavy ion beam (HIB) [4] (driver energy is 7 MJ with 20.4% efficiency). Repetition rate is calculated by given driver energy and pellet gain. Chamber size is approximated by some other reactor designs [3, 4]. Cost of plant systems except for driver system and pellet production are calculated by the same scaling as PEC code. Driver system and pellet production cost are given by the scaling described in Ref. [4].

To estimate CO₂ emission amounts, we used basic unit for CO₂ weight (k-t-CO₂/t-material) [2, 5, 6]. CO₂ emissions from mining, transport and fabrication are included in this factor.

3. Assessment models
Models of confinement systems and blanket models adopted here are explained below. To compare all of fusion reactors...
reactors under the same conditions, 1000MW(e) net electric power output, 30 years operation period and 0.75 utilization factor are assumed.

In the reference case normalized beta value (average beta value for HR) is determined by the technical performance of reactor models which is considered now. When TR employs D-3He fuel, high temperature and high maximum toroidal field is required to design sufficiency compact and economical reactor. So D-3He fuel reactor is assumed to have high performances (high temperate, magnetic field and beta). Because of the low neutron generation rate of D-3He fuel, we assumed that there is no blanket exchange during D-3He fuel fusion reactors. Main parameters of magnetic confinement fusion reactors calculated by PEC code are listed in Table1.

Pellet gain of IR is given as an input in our calculation. And pellet gain is selected same value for Kr-F laser system reactor and HIB reactor. Li breeder liquid wall chamber is adapted to IR and we assumed that there is no blanket exchange during its operation period. The main parameter of the reference case of IR is listed in Table2.

Blanket modules we adapted to TR are Li breeder with V structural material blanket (Li/V), Flibe breeder with ferrite steel structural material blanket (Flibe/FS), LiPb breeder with SiC structural material blanket (LiPb/SiC), Li2O breeder with SiC structural material blanket (Li2O/SiC) and fission fusion hybrid (F-F hybrid) blanket [7]. There is UO2 in F-F hybrid blanket model so its neutron energy multiplication rate is very high (We assumed 6.0). Each model has a difference in thermal efficiency and wall life time in PEC code [2]. Main parameter of the TR reactor which has different blanket is shown in Table3.

4. Results

The CO2 calculation results of reference fusion reactors are shown in Fig.2. The coil construction phase is the most CO2 emitting stage of magnetic confinement fusion reactors. CO2 emission amounts from coil system construction account for 10%, 8% and 20% of lifetime CO2 emission amount of TR, ST and HR, respectively. HR and D-3He fuelled TR needs rather larger coil than D-T fuelled TR and ST, and more CO2 are emitted at the Fusion Island (FI) construction stage. ST needs more re-circulating power including ohm loss at the normal conducting coil, and more CO2 are emitted at the Balance of Plant (BOP) construction stage. On the contrary, HR requires less re-circulating power, and less CO2 is emitted at the BOP construction stage. Dependence of CO2 emission amount and plasma major radius on beta value is shown in Fig.3. The achievement of higher beta value leads to more compact system and less CO2 emission.

CO2 emission amounts of tokamak reactors with different blanket module are shown in Fig.4. Thermal efficiency is an influential factor to design fusion reactor. A
higher thermal efficiency model, such as LiPb/SiC or Li2O/SiC model, can give rise to more compact system and less CO2 emission than other blanket models. Vanadium needs much electric power to fabricate, so the CO2 emission amount of Li/V blanket model is rather higher than others. F-F hybrid blanket model modify FI requirements because of its high neutron multiply factor. Therefore it is possible to construct with lower cost and less CO2 emission amount. But there exists another problem; high level radioactive waste disposal. Driver construction stage is the most CO2 emitting stage of IR. Additionally IR emits more CO2 than magnetic confinement fusion reactor at the fuel cycle stage. However, total CO2 emission amount from IR is lower than that from magnetic confinement fusion reactors because of its compactness and the assumption that no blanket exchange is required during its operation period. Dependence of CO2 emission amount, laser repetition rate and chamber size on pellet gain is shown in Fig.5. When pellet gain is low, high laser repetition rate is necessary to attain desired net electric power. High laser repetition rate requires many pellets, and CO2 emission during fuel cycle is increased. Whereas, when high pellet gain is assumed, large chamber size is necessary to tolerate high fusion heat pulse. Figure 6 shows the comparison of fusion power plants and other power generation systems from the view point of COE and CO2 emission amount. Comparison among fusion reactors and other conventional power plants from the aspect of COE and CO2 emission amount. COE of fusion reactor and other power plants in the case of carbon tax introduction is shown in Fig.7. CO2
emission amount from fusion reactor during its life time is far less than those from thermal power plants. Introduction of carbon tax has little impact on COE of fusion reactors alike conventional clean energy resources like solar and wind power etc. Carbon taxes assumed here are 1350, 3808, 655 and 2300 yen/kWh (actual example of Norway, actual example of Sweden, a plan of Japanese environment ministry and recommendation of Central Research Institute of Electric Power Industry [8], respectively.)

5. Conclusion

We calculated CO₂ emission amount from various fusion reactors including inertial confinement fusion reactor. CO₂ is emitted mainly at the magnet system construction stage for magnetic confinement fusion reactors. So HR and D-3He fuelled fusion reactors with bigger magnet system emits more CO₂ during its construction stage. FI of ST is so compact that CO₂ is less emitted during its construction, but BOP construction stage involves much CO₂ emission because of its large re-circulating power. For inertial confinement fusion reactors CO₂ is emitted mainly at the driver system construction stage. The chamber size and quantity of pellet decided by repetition rate are also strongly related to CO₂ emission amount. After comparing fusion reactors with other power generation systems from the view point of CO₂ emission amount, we conclude that fusion reactor emits less CO₂. There is little influence on economics of fusion reactors even by introducing carbon tax.

References