EVALUATION OF CO_2 EMISSION IN THE LIFE CYCLE OF TOKAMAK FUSION POWER REACTORS

K.TOKIMATSU[*], H.HONDO[#], Y.OGAWA, K.OKANO[##], K.YAMAJI, and M.KATSURAI
The University of Tokyo, School of Engineering, 2-11-16, Yayoi, Bunkyo-ku, Tokyo, Japan 113
[#] CRIEPI (Central Research Institute of Electric Power Industry)
Socio-economic Research Center, 1-6-1, Ohtemachi, Chiyoda-ku, Tokyo, Japan 100
[##] CRIEPI (Central Research Institute of Electric Power Industry)
Komae Research Laboratory, 2-11-1, Iwadokita, Komae-city, Tokyo, Japan 201

Abstract

Global warming problem is one of the most serious problems which human beings are currently face. Carbon Dioxide (CO_2) from power plants is considered one of the major causes of the global warming. In this study, CO_2 emission from Tokamak fusion power plants are compared with those from conventional present power generating technologies. Plasma parameters are calculated by a systems code couples the ITER physics, TF coil shape, and cost calculation. CO_2 emission from construction and operation is evaluated from summing up component volume times CO_2 emission intensities of the composing materials. The uncountable components on such as reactor building, balance of plants, etc., are scaled from the ITER referenced power reactor (ITER-like) by use of Generomak model. Two important findings are revealed. Most important finding is that CO_2 emissions from fusion reactors are less than that from PV, and less than double of that from fission reactor. The other findings are that (i) most CO_2 emissions from fusion reactors are from materials, (ii) CO_2 emissions from reactor construction becomes almost 60 % to 70 %, rest from reactor operation, and (iii) the RS reactor can reduce CO_2 emission half compared with the ITER-like reactor. *In conclusion, tokamak fusion reactors are excellent because of their small CO_2 emission intensity, and they can be one of effective energy supply technologies to solve global warming.*

---

[*] First author's present affiliation; RITE (Research Institute of Innovative Technology for the Earth);
7th Floor, No.3 Toyokaiji Bldg., 2-23-1, Nishi-shimbashi, Minato-ku, Tokyo, 105-0003, JAPAN
e-mail: toki@rite.or.jp, toki@katsurai.t.u-tokyo.ac.jp. This paper is based upon his Ph.D. thesis, the Univ. of Tokyo (1998),

1. INTRODUCTION

Global warming problem is one of the most serious environmental problems that human being currently face. The mechanism of global warming is not clearly understood, however, global warming is considered inevitable if emission trend of anthropogenic greenhouse gas such like CO_2, methane CH_4 will continue in 21st century. Various countermeasures such as technological developments, economical mechanism abatement policies, international negotiations etc, are proposed and carried out. CO_2 emission is related to all human activities that are supported by energy consumption via mainly fossil fuels. CO_2 emission from electric power plants is one of the major emission sources. In order to evaluate energy consumption and associated CO_2 emission due to human activities or energy supply technologies; such studies of Ref. 1 for industrial/economic activities or Ref. 2 for electric power plants have been investigated.

Although we can find reactor studies [3-8], reactor system studies for reducing COE (Cost Of Electricity) [9-12], and reactor cost comparison studies with other power plants [13,14], no study could be found to evaluate CO_2 emission from nuclear fusion power plants. In this study, CO_2 emissions from tokamak fusion power reactors due to their construction and operation during their plant lifetime are evaluated on the basis of tokamak reactor system studies and compared with other energy technologies.

2. POWER PLANT PROPERTIES

Two types of fusion power reactors are evaluated whose reactor parameters are listed in Table 1. One is a power reactor ITER-like that is powered up from the ITER device, and the other is a reversed shear operating mode reactor. Plasma parameters of the ITER-like reactor [11,12] are obtained by minimum modification from those of the ITER device using our systems code [15,16]. The parameters of the RS reactor are also obtained in Ref. [11,12], which are similar to those of the CREST (Compact REversed Shear Tokamak) reactor [8]. 1000 MW of electric power at bus bar P_e, 75% of plant availability, 30 years of plant life, are characteristics of the fusion power reactors. The fusion power range is from about 3 to 4 GW with thermal to electricity conversion efficiency of the 34.5 % using water as a coolant. Ferrite steel is assumed for the structural material. A shield blanket for the ITER-like, and a breeding blanket for the RS reactor is assumed, respectively. Weight fractions of structural materials, Tritium breeder Li_2O, and neutron multiplier Be in the breeding blanket are set which are referred from the SSTR (Steady State Tokamak Reactor) [17]. Weight calculation of PF (Poloidal Field) coils, miscellaneous, and support structures is set which are referred from the ITER-TAC4 report [18].

Other power plant properties, which are referred from Ref. 2, are shown in Table 2. All these power plants are based upon Japanese conventional power plants. No plutonium recycle (once-through), gas-diffusion type uranium condensation are applied for a fission reactor. A house-use type photo voltaic (PV) is considered. Total electric output of other power plants are all 1000MW. Therefore, bus bar electric power is slightly smaller by re-circulation power, however, these plants bus bar are almost the same as those of the fusion reactors.

TABLE I. REACTOR PARAMETERS USED IN THIS STUDY

	Reactor types		
	ITER	**ITER-like**	**RS**
Structural material	SUS	Ferrite	Ferrite
Coolant	Water	Water	Water
Conversion efficiency (%)	34.5	34.5	34.5
Plasma major radius (m)	8.4	8.4	5.1
Aspect ratio	2.91	2.91	3.0
Elongation	1.6	1.8	2.0
Triangularity	0.24	0.24	0.5
Toroidal field on TF coil (T)	12.5	12.5	13.0
Toroyon coefficient	2.2	2.7	4.95
H-factor (ITER89P)	~2.6	1.424	2.289
Plasma temperature (keV)	10.5	20	15
Safety factor on 95%	3.0	3.0	3.75
Plasma current (MA)	21.0	27.6	15.5
Bootstrap current fraction		0.289	0.935
Current drive power (MW)	70	263.1	23.5
Neutron wall load (MW/m^2)	1.5	2.371	4.287
Fusion power (MW)	1500	4034	2879
Total thermal power (MW)		4699	3239
Electric output power (MW)	---	1000	1000

TABLE II. POWER PLANTS PROPERTIES

	Fusion		**Fission** (once-through, gas-diffusion type)	**Coal fired**	**Water powered**	**Photo-Voltaic** (for a house use)
	ITER-like	RS				
Total output electric power (MW)	1621	1117	1000	1000	10	0.003
Re-circulation power fraction (%)	38.3	10.5	3.4	7.4	0.25	0
Electric power at bus bar (MW)	1000	1000	966	926	9.975	0.003
Plant availability (%)	75	75	75	75	45	15
Plant lifetime (years)	30	30	30	30	30	30

3. CO_2 EMISSION EVALUATION

3.1 Applied method

As shown in Fig. 1, there are two streams, fuel and material, which compose input energy for plants. In these two streams, processes consist of mining, refining, manufacturing, disposal, and the transportation connecting these four processes. All the materials and energy have to be considered each process. We used the bottom up method which sums up all the energies used for fuel and materials.

In this study, reactor construction, replacement within plant lifetime, and fuel consumption are considered, which is shown in Table 3. Only manufacturing energy for fuel is considered, i.e., no consideration is given to mining. Energy for fuel refinement and transportation, because of the difficulty of evaluating this energy, is assumed to be 20 % of fuel refinement energy, as in Ref. [2]. Self-sufficient initial tritium and deuterium consumption (about 0.3kg/day for a 1 GWe reactor) are assumed. CO_2 emission intensity for deuterium is based upon Ref. [19], and that of tritium is assumed to be the same as that of deuterium.

Regarding material flow, energy for raw mineral mining and refining cannot be considered because of a lack of existing data. Required energy for manufacturing materials (material energy) from raw material, via intermediate material, to final material is calculated by multiplying weight and energy intensity together. Manufacturing energy, which is required in manufacturing components from final material to component, is evaluated by manufacturing cost [18]. Cost data of the ITER cost estimation are used as much as possible because of their reliability. Construction and transportation energy is assumed to be 20 % of the sum of material energy and manufacturing energy.

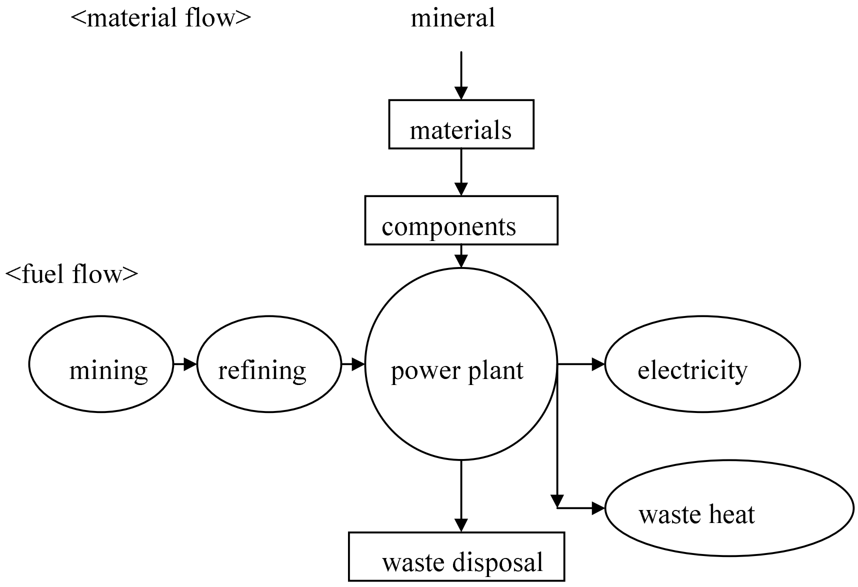

FIG.1 There are two flows for life cycle analysis (LCA) of power plants; one is for material, the other is for fuel.

TABLE III. INCLUSION AND METHOD OF INPUT ENERGY FOR FUEL AND MATERIALS

Fuel			Materials		
Process	**Inclusion**	**Method**	**Process**	**Inclusion**	**Method**
Mining	no		Mining and Refining of minerals	no	
Manufacturing	yes	CO$_2$ Emission Intensity x Fuel consumption	Material	yes	CO$_2$ Emission Intensity x weight or cost
Refining	yes	20% of manufacturing	Manufacturing	yes	Cost
Transport			Construction Transportation	yes	20% of material and manufacturing
Consumption	yes	Deuterium : 0.3 kg/day Tritium : self-sufficient is assumed	Replacement	yes	Blanket/Current Drive: Neutron wall load and neutron fluence
					Divertor : every year replacement
					All the others : One time of whole replace-ment within plant life time

3.2 Applied data

CO$_2$ emission intensity data, which is listed in Table 4, are derived from energies consumed during processes like the manufacturing. Energy consumption data of NbTi strands, SUS alloy, Ferrite alloy, and Copper alloy are referred from Ref. [20] which describes the energy analysis of a Super-GM (a motor-generator using superconductor). Data of deuterium is derived from Ref. [19]. Deuterium is assumed to be obtained from nitrogen and hydrogen by an ammonia-hydrogen dual temperature exchange process in ammonia plants. Other materials/components such as concrete, blister steel, are referred from Ref. [1] that were derived from present input-output table (I/O table). Weight of a neutral beam injector (NBI) device is derived from that of SSTR and that of JT-60U. Since CO$_2$ emission intensity data of NBI device do not exist, the second highest energy consumption per unit weight data described in Ref. [1] for the NBI in order to make a severe assessment.

Energy consumption data for Li$_2$O used for the blanket is evaluated using the latest data of Li extraction from seawater (10000 kWh for Li$_2$CO$_3$ 1 ton) [21]. Energy consumption data for special materials such as, Vanadium-alloy, Be and SiC are soused from Refs. [19,22]. Titan in Ref. [22] is applied for Vanadium-alloy. For R.B. (Reactor Building), unalloyed steel used in the reactor plant equipment in Ref. [23] (2086 ton) is included in the reactor building. For the B.O.P. (Balance of Plant), both unalloyed steels and high alloyed steels for “structure + site facilities”, turbine plant equipment, and misc.

plant equipment (total amount = 43656 ton (Ref. [23])) are considered. In addition to the steel, concrete (Japanese fission experience = 983390 ton (Ref. [2])) is counted as a part of the B.O.P. Electric equipment used in a power plant is also included for heat transportation, current drive system, R.B., and B.O.P. by use of cost.

Cost of current drive is a product of heating power and unit heating cost. Cost of Heat Trans, R.B. and B.O.P. is a product of standard cost and scaling factor. The unit cost of heating power is set 4.6 \$/W [24] referred from the SSTR. The standard costs of Heat Trans, R.B., and B.O.P. are decided by re-categorizing the ITER-IDR [25] cost items following the Generomak model [26].

TABLE IV. ENERGY INTENSITY AND CO$_2$ EMISSION INTENSITY OF EACH COMPONENT

Items	Materials for reactors		Materials applied for this study	CO$_2$ Emission(a) Intensity
Superconductor Coils	Nb$_3$Sn strand		NbTi strands(c)	30.7
	SUS316 (Fe66, Ni22, Cr18, Mn2, Mo2)		SUS alloy(c) (Fe31.2, Ni33, Cr30.7)	7.5
Blanket **Shield** **Divertor**	Structural Materials	SUS316	SUS alloy	7.5
		Ferrite (HT-9) (Fe87, Cr8, W1)	Fe-Ni-Cr alloy(c) (Fe86.5, Ni9, Cr3)	8.7
		Vanadium (V-5Cr-5Ti) (V90, Cr5, Ti5)	Ti64(d)	83.7
		SiC (Si50, C50)	SiC(e)	14.0
	Cu-alloy		Cu99, Cr1(c)	3.2
	Li$_2$O		Li2, O1(f)	9.68
	Be		Be(e)	240.8
Reactor Building	Unalloyed steels (2086 ton)		Blister steel(g)	1.41
Balance of Plant	Electrical equipment		Electrical equipment(g)	344.3 (b)
	High alloyed steels (43656 ton)		Blister steel	1.41
	Concrete (983390 ton)		Concrete(g)	0.11
Heat Trans	Electrical equipment		Electrical equipment	344.3 (b)
Current Drive	SUS etc.		electric computer(g)	21.3

Unit: (a) t-CO$_2$/t-material, (b); t-CO$_2$/M\$

References: (c) Ref.[20], (d) Ref.[22], (e) Ref.[19], (f) Ref.[21], (g) Ref.[1]

4. RESULTS

4.1 Comparison with other energy sources

CO$_2$ emission intensity results of these fusion reactors are compared with other energy sources in Figure 2. Results of other energy technologies are referred from Ref. [2]. Evaluation methods and premises of other energy technologies are the same as those of fusion reactors. Both once-through method for nuclear fuel usage and gas diffusion method for fuel condensation are assumed for a fission rector. A conventional house-use photo voltaic

(PV) installed on house-roof is considered. Manufacturing energy, which is required in manufacturing components, is not included in the fusion energy gain results because this manufacturing energy is not included in all the other energy sources.

CO_2 emission from the ITER-like is much less than those from fired power plant, slightly better than that from PV, and two times as much as that from the fission reactor. However, the enhanced physics RS reactor can reduce the CO_2 emission to the half of that of the ITER-like, which result in closer to those of fission or hydro-powered generation. Hence, CO_2 emission per unit electricity from the RS reactor is small, compared among present electric power sources.

Either the fission reactor (by plutonium recycling and centrifugal technique) or PV (by increment of electricity and cell effect, decrement of cell thickness) has possibility to reduce CO_2 emission by half. Therefore, CO_2 emissions from fusion reactors are slightly less than that of PV, and about double of that of fission reactor if advanced physics or technologies are assumed for fusion, fission, and PV. CO_2 emissions from these three energy technologies are in anyway, concluded little compared with energy technologies using fossil fuel.

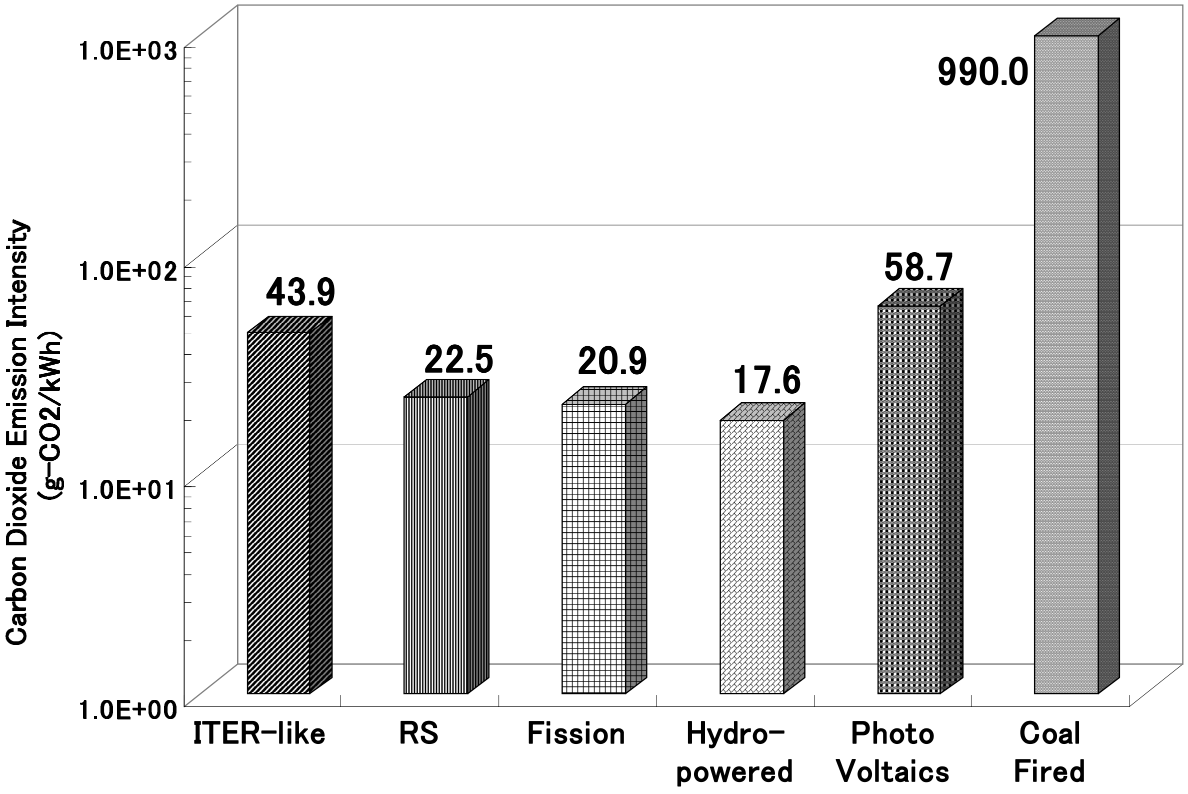

FIG. 2. Power plants comparison of CO_2 emission per unit electricity. CO_2 emission from the ITER-like, the RS reactor is comparable to that from a PV system (for a house use) and a fission reactor (once-through, gas diffusion type), respectively.

4.2 CO_2 emission breakdowns

The breakdowns of CO_2 emission from the fusion reactors are indicated in Figure 3. Breakdowns of the bar graphs are from the bottom (1) coils and their support structure, (2) blanket/shield/divertor, (3) current drive (CD), (4) heat transportation (Heat Trans), (5) reactor building (R.B.), (6) balance of plant (B.O.P.), (7) replacement (blanket, divertor, current drive, and center post for ST from the bottom) and (8) fuel.

The result characteristics of CO_2 emission of tokamak fusion reactors are follows. (1) Most CO_2 emissions from fusion reactors are from materials, CO_2 emission from fuel consumption is negligible. (2) CO_2 emission from reactor construction, corresponding to those of all the breakdowns except fuel and replacement, becomes almost 60 to 70 %, while CO_2 emission due to operation equals 30 to 40 %. (3) The RS reactor, compared with the ITER-like reactor, can reduce CO_2 emission half through compacting reactor size by physics performance enhancement.

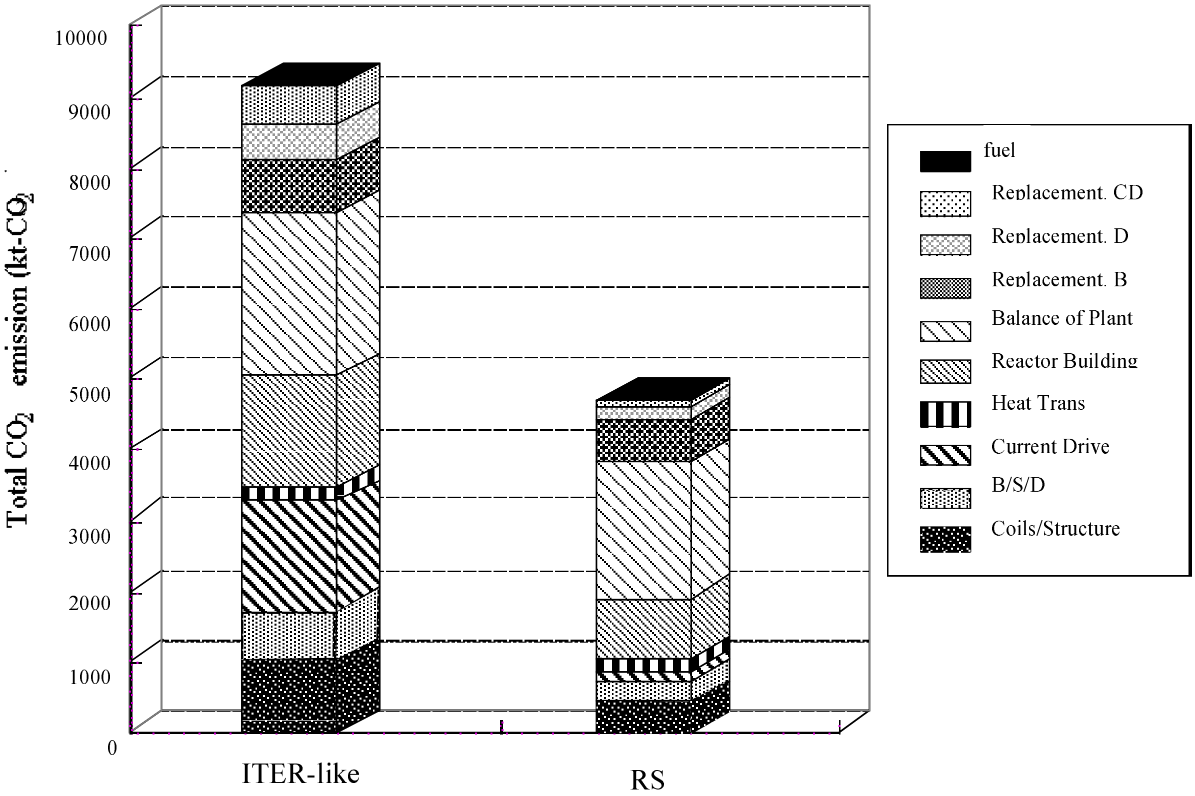

FIG. 3. Comparison of the CO_2 emission in the life cycle of the ITER-like and the RS reactors. Following two points can be pointed out. (1) CO_2 emission from fuel consumption can be neglected. (2) CO_2 emission due to replacement increase up to 20 to 30 %.

5. CONCLUSION

In this paper, CO_2 emissions in the life cycle of tokamak power plants are evaluated. Evaluation methods and premises of fusion reactors are the same as that of other energy technologies that are referred from Ref. [2]. Through this study, we reveal following two things.

Most important finding is that CO_2 emissions from fusion reactors are less than that from PV, and less than double of that from fission reactor. The other findings are that (i) most CO_2 emissions from fusion reactors are from materials, (ii) CO_2 emissions from reactor construction becomes almost 60 % to 70 %, rest from reactor operation, and (iii) the RS reactor can reduce CO_2 emission half compared with the ITER-like reactor.

In conclusion, tokamak fusion reactors are excellent because of their small CO_2 emission intensity, and they can be one of effective energy supply technologies to solve global warming.

REFERENCES

[1] HONDO, H., “Energy Requirements and CO_2 Emissions in the Production of Goods and Services: Application of an Input-Output Table to Life Cycle Analysis”, CRIEPI (Central Research Institute of Electric Power Industry) rep. No. Y95013, (1996) (in Japanese).

[2] UCHIYAMA, Y., “Life Cycle Analysis of Power Generation Systems”, CRIEPI (Central Research Institute of Electric Power Industry) rep. No. Y94009, (1995) (in Japanese).

[3] SEKI, Y., et al, 13th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, 1990 (Proceedings of 13th Internarional Conference in Washington,1990), Vol.3, IAEA, Vienna (1992)473.

[4] CONN, R.W., et al., 13th International Conference on Plasma Physics and Controlled Nuclear Fusion 1990 (Proceedings of 13th Internarional Conference in Washington,1990), Vol.3, IAEA, Vienna (1992)659.

[5] NISHIO, S., et al., Fusion Engineering and Design **25** (1994) 289-298. (The Concept of Drastically Easy Maintenance (DREAM) Tokamak Reactor)

[6] INOUE, N. et al., in 14th International Conference on Plasma Physics and Controlled Nuclear Fusion Research 1992 (Proceedings of 14th Internarional Conference in Wurzburg,1992), Vol.3, IAEA, Vienna (1992)347.

[7] The SEAFP Project, (Safety and Environmental Assessment of Fusion Power), Report of SEAFP Project , June (1995).

[8] OKANO,K., et al., to be appeared in these papers (IAEA-CN-69/FTP11)

[9] BATHKE, C.G., “A preliminary systems assessment of the Starlite demo candidates”, 16th Symposium on Fusion Engineering (SOFE-16) (1995).

[10] GALAMBOS, J.D., et al., “Commercial tokamak reactor potential with advanced tokamak operation”, Nuclear Fusion **35**(1995)551.

[11] TOKIMATSU,K., OKANO,K., YOSHIDA,T., YAMAJI,K., and KATSURAI,M., “Study of design parameters for minimizing the cost of electricity of tokamak fusion power reactors”, Nuclear Fusion **38** (1998) 885.

[12] TOKIMATSU,K., “Quantitative Analysis of Economy and Environmental Adaptability of Tokamak Fusion Power Reactors”, Ph.D. thesis, The University of Tokyo, 1998.

[13] KRAKOWSKI, R.A., and DELENE, J.G., “Connection between physics and economics for tokamak fusion power plants”, Journal of Fusion Energy **7**(1988)49.

[14] MILLER, R.L., ”Economic goals and

requirements for competitive fusion energy", in 4th International Symposium on Fusion Nuclear Technology (Abstracts of the ISFNT-4), Fusion Engineering Division of Atomic Energy Society of Japan and Nuclear Engineering Research Laboratory of The University of Tokyo, Tokyo (1997).

[15] YOSHIDA, T., et al., "Development of Cost Assessment Code of Fusion Power Reactors, T94001, Komae Research Laboratory, CRIEPI (Central Research Institute of Electric Power Industry) (1994) (in Japanese).

[16]HATAYAMA, A., et al., 'Basic requirements for a 1000-MW (electric) class Tokamak Fusion-Fission Hybrid Reactor and its Blanket concept', Fusion Technology **26** (1994) 27.

[17]Reactor design laboratory, Concept Study of the Steady State Tokamak Reactor (SSTR), JAERI-memo 03-058, 1991, (in Japanese).

[18]Detail of the ITER Outline Design Report (The ITER-TAC4 report), San Diego Joint Work Site, (1994).

[19] KOZAKI, Y., "Analysis for realization of fusion reactors", The Institute for Future Technology, 1978, unpublished, (in Japanese).

[20] Science and Technology Agency, "Assessment for Superconductor Technique of Resources and Energy" (1987) (in Japanese).

[21] OHI, K., Shikoku National Industrial Research Institute (Takamatsu, Japan), private communication, 1997.

[22] SHIMAZU, Y., "FUSION REACTOR SYSTEM ASSESSMENT MANUAL", Report of Energy special study (fusion) funded by Ministry of Education, Nagoya University, Japan (1986) (in Japanese).

[23] BUNDE, R., Nuclear Engineering and Design/Fusion **3**(1985)1.

[24] YOSHIDA, T., CRIEPI(Central Research Institute of Electric Power Industry, Tokyo, Japan), private communication, 1997.

[25] INTERNATIONAL ATOMIC ENERGY AGENCY, Technical Basis For The ITER Interim Design Report (ITER-IDR), Cost Review and Safety Analysis, ITER Project Cost Estimate, IAEA, Vienna (1996).

[26] SHEFFIELD, J., et al., Fusion Technology **9**(1986)199