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Journal of Nuclear Materials 258–263 (1998) 1589–1593

journal of nuclear materials

A fusion power reactor concept using SiC/SiC composites

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Abstract

JAERI studied a concept of a commercial fusion power reactor (5.5 GW, electric output: 2.7 GW) having high environmental safety, high thermal efficiency and high availability. The reactor configuration was designed to achieve good maintainability, high performance breeding blanket, high efficiency power generation system and less radwastes. The design was based on the use of low activation structural material (SiC/SiC Composites) and helium as a coolant. (1) Easy maintenance is attained by sector replacement with the radiation environment less than 10^3 R/h in a reactor chamber. (2) The net thermal efficiency over 45% is attained by high temperature helium gas Brayton cycle. (3) Most of radwastes of DREAM reactor can be disposed in shallow land burial as a low level radwaste after cooling of several tens of years.

1. Introduction

JAERI studied a concept of a commercial fusion power reactor (5.5 GW, electric output: 2.7 GW) having high environmental safety, high thermal efficiency and high availability. The reactor configuration was designed to achieve good maintainability, high performance breeding blanket, high efficiency power generation system and less radwastes. Design was based on the use of low activation structural material (SiC/SiC Composites) and helium as a coolant.

Various types of fusion reactor design concepts such as ARIES-1 [1], SSTR [2], IDLT [3], FFHR [4], ARIES-RS [5], CREST [6] have been proposed. However, the fusion reactor concepts which emphasize advantage of low activation material on maintainability and radwastes are limited. JAERI has already proposed the proto-type fusion reactor concept, SSTR, as a fusion reactor concept which has played a great role in promoting plasma physics research. In this concept the ferritic steel, F82H and water were adopted as the in-vessel structural material and coolant, having already a base of industrial scale fabrication. However, the SSTR requires the robust design against electromagnetic loads at disruptions and the development of maintenance tools to be used at high radiation dose. Therefore, the authors tried to make an advanced concept of a fusion reactor from the viewpoint of plant availability, thermal efficiency, and maintenance environment. This concept was named drastically easy maintenance tokamak reactor (DREAM) [7].

2. Design guideline

The authors determined the following design requirements for developing the DREAM reactor concept.

1. Reactor configuration allowing easy access for maintenance.
2. Improvement of radiation environment for maintenance equipment.
3. High environmental safety from the view point of radwaste disposal.
4. High thermal efficiency by high temperature gas turbine.

Based on these design requirements, the following design approaches were considered.

(a) As SiC/SiC composites are very low activation materials, the activation dose level in the reactor torus

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0022-3115/98/$19.00
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can be reduced by five orders of magnitude compared with stainless steel, SUS316 one day after reactor shutdown. The radiation dose level in vacuum vessel is lower than 1000 R/h.

(b) Using the high insulation resistance of the SiC/SiC composites, electromagnetic loads acting on in-vessel components are significantly reduced and the design load for support structures is mitigated.

(c) The torus system is divided into 16 equal sectors. The blanket and divertor sectors are removed independently by a single radial straight movement between the adjacent toroidal coils.

(d) The module type of blanket vessels are designed and assembled into the blanket sector. This concept simplifies the design and manufacturing process of the blanket.

(e) The torus configuration with a high aspect ratio is selected. All coolant piping systems are extracted into the inner side of the torus region. The outer side of the torus region can be used for easy maintenance operation.

(f) The high temperature helium gas cooling system is adopted to achieve a high thermal efficiency and safety.

(g) The mass power density is designed to be 150 kW/ton to get the economical scale merit.

3. The plasma design parameter, configuration and maintenance

The whole layout and the major parameters of DREAM tokamak are shown in Fig. 1 and Table 1, respectively. DREAM reactor is operated in a steady-state mode. The plasma major radius is 16 m and the aspect ratio is 8. A plasma operation at high aspect ratio brings a high self-induced bootstrap current and therefore, a rather small capacity of neutral beam injection (NBI) is enough. NBI current drive power necessary for the steady-state operation is about 50 MW. As the DREAM reactor has no metal shell near the plasma, a small elongation of 1.3 is adopted and operated in the first stability regime. A relatively small radius of 2 m is found to produce 5.5 GW of fusion power using a toroidal field of 20 T. The divertor condition of DREAM reactor is estimated using a two point model, scaling formula and a simple 2-D edge plasma code. The maximum heat flux and electron temperature were evaluated to be less than 5 MW/m^2 and 100 eV, respectively.

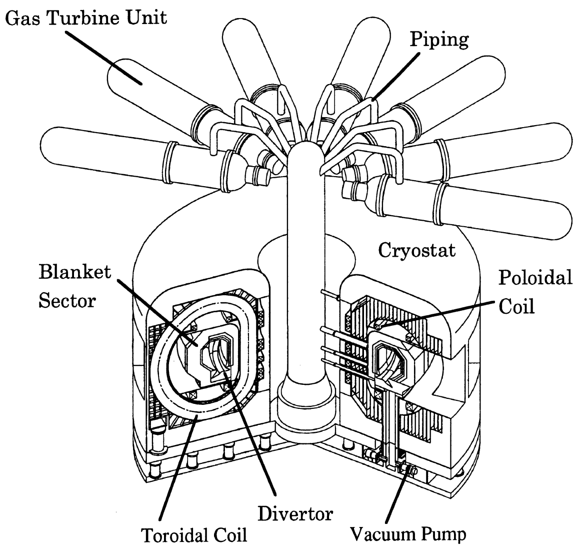

Fig. 1. Configuration of the DREAM reactor.

Table 1
Design parameters of the DREAM reactor

Term	Specification
Major radius	16 m
Minor radius	2 m
Plasma current	9.2 MA
Toroidal field	14 T
Troyon coefficient	3
Mean density	1.65×10^{20} m^{-3}
Bootstrap current fraction	87%
Current drive power	50 MW (NBI)
Fusion power	5.5 GW
Thermal power	6.12 GW
Net electric power	2.73 GW
Maximum neutron wall load	5 MW/m^2

The torus structure is divided into 16 sectors. In each sector, the blanket assembly and divertor cassette can be removed independently by a single radial straight movement between the adjacent toroidal coils. This configuration is shown in Fig. 2. Blankets are replaced periodically every 2–4 years. Divertor cassettes are unplanned maintenance components in the DREAM Reactor. Therefore, these components are designed to be removed from the reactor independently. When these components are removed for maintenance, cask type removal machines are used to protect scattering of radioactive dusts produced in the reactor torus. Removed components are maintained in the hot cell next to the reactor room.

4. Material properties of SiC/SiC composites

When designing the in-vessel components, material properties of SiC/SiC were determined as shown in Table 2. The properties of SiC/SiC composite were assumed to be homogeneous. The thermal conductivity is 15 W/m K in the normal component including the first wall of the blanket and 60 W/m K for the divertor plate. The values are one, after neutron irradiation of 10 MWa/m^2 neutron wall load. The value of 15 W/m K is

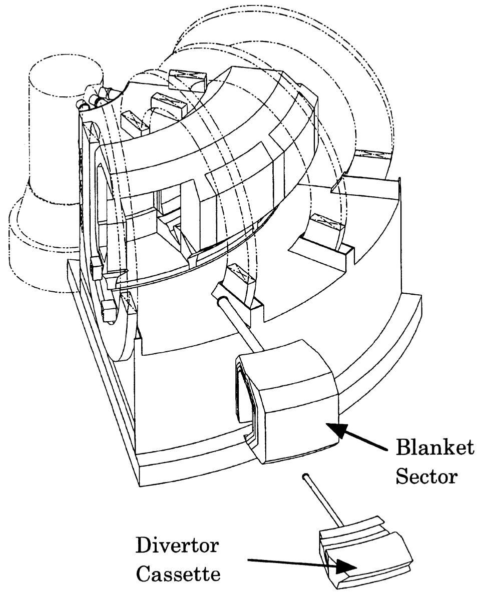

Fig. 2. Concept of replacement of blanket and divertor.

Table 2
Design value of SiC/SiC composites

Term	Design value
Young's modulus	200 GPa
Poisson ratio	0.2
Thermal expansion coef.	3.3×10^{-6} /K
Thermal conductivity	
Normal component	15 W/m/K
Divertor plate	60 W/m/K
Stress limit	200 MPa
Allowable temperature	1100°C

the target in the near future of SiC/SiC development plan in JAERI. A value of 15 W/m K is used in the TAURO breeder blanket design [8]. The value of 60 W/m K is used for the divertor plate. If the 60 W/m K is difficult to be realized in the near future, C/C composites and tungsten are considered as the substitute candidate materials, although the radiation dose level inside the tokamak vessel becomes much higher. When tungsten is used, the dose in reactor torus at maintenance operation must be evaluated.

5. Blanket design

A bird's eye view and sectional view of a blanket module are shown in Figs. 3 and 4. The module is composed of the first wall, neutron multiplying region, tritium breeding region, and high temperature radiation shielding region in the order as shown in Fig. 4. The size

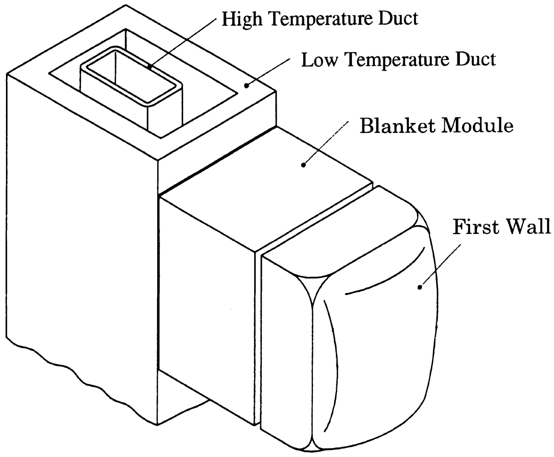

Fig. 3. Schematic of blanket module.

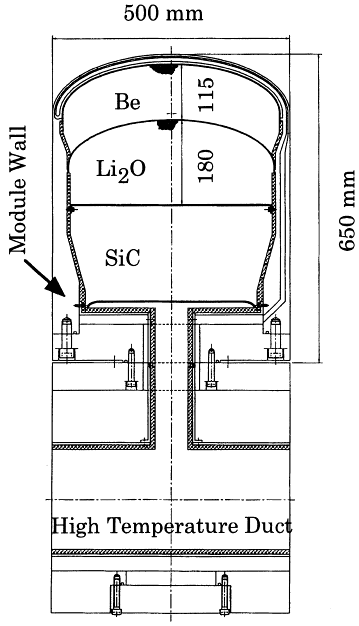

Fig. 4. Sectional view of blanket module.

of a blanket module is about 0.5 m × 0.5 m and the height is 0.65 m. The structural material of the blanket module is SiC/SiC composite. The manufacturing procedure of the blanket module is shown in Fig. 5. The module is made by forming SiC fabric, by sintering and curing processes. Assembling of blanket vessel is done using SiC/SiC bolts because of the lack of a good joint method between the parts at present. About 400 modules are assembled to make a blanket sector. The beryllium pebble of 1 mm diameter is used as neutron multiplier. The Li_2O pebble is used as the tritium breeder from the view point of low activation and triti-

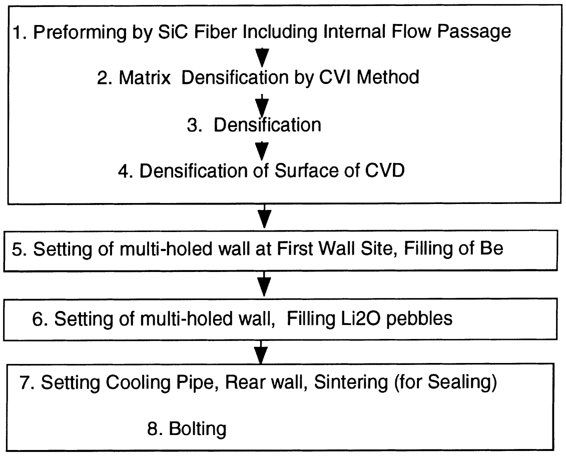

Fig. 5. Manufacturing procedure of blanket module.

um breeding performance. The coolant gas is helium and its pressure is 10 MPa. The high pressure helium is sealed by metallic gaskets at bolting joints as shown in Fig. 4. Metallic gaskets are made from Inconel alloy and the maximum operation temperature is 800°C. The helium gas flows up to the first wall along the outer vessel wall from the inlet pipe and temperature rises up to 700°C in the first wall. After that the helium gas flows into the inner region of the module to cool the three regions and the temperature rises up to 900°C at the exit of the module. The thickness of beryllium layer, lithium oxide layer, and SiC/SiC high temperature layer was determined and optimized to obtain the local tritium breeding ratio over 1.3, following the criteria of radiation shielding against the superconducting toroidal coil. However, the net tritium breeding ratio becomes 1.1 because of the neutron flux distribution and blanket coverage. The helium coolant also has the role of sweeping gas to recover the produced tritium.

6. Power generating system

The DREAM reactor uses helium gas Brayton cycle power generation system. The helium gas pressure is 10 MPa. The inlet temperature of helium gas of 600°C and outlet temperature is 900°C inside the blanket. In addition, the heat removed from the divertor is also used to increase the thermal efficiency. Twelve gas turbine modules of 500 MW are designed. The net thermal efficiency is 47%. The tritium recovery system is placed between the exit line from the gas turbine modules and the inlet line to blanket modules. The 0.15% of helium gas bypass flow to the tritium recovery system is sufficient to keep the mobile tritium inventory of the power generating system below 100 g.

7. Safety considerations

The activation dose inside the vacuum chamber at maintenance, radwastes, and the temperature rise of the first wall at loss of coolant accidents were investigated.

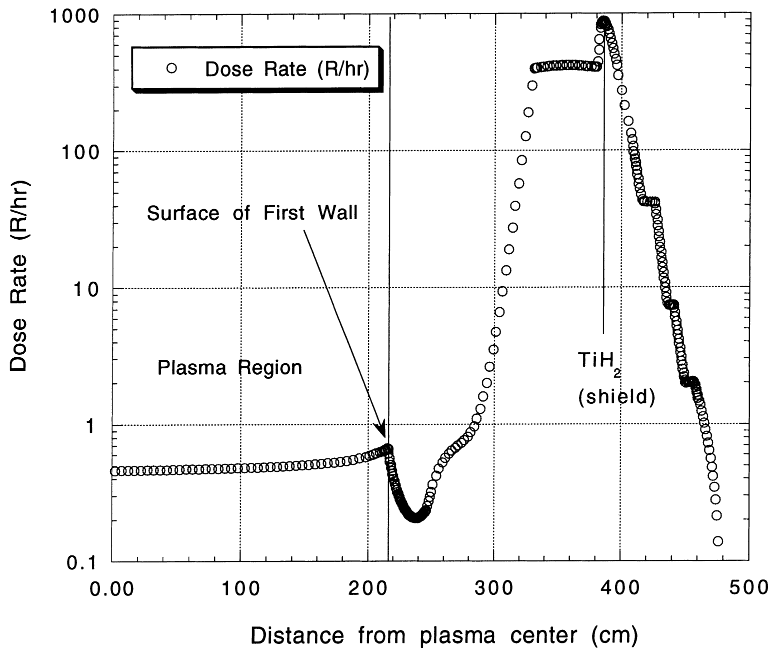

Fig. 6. Dose rate distribution in a radial direction inside the tokamak reactor.

The activation dose analyses were done using the ANISN [9], and FISPACT [10] codes. The calculated radiation dose distribution along the inboard radial build is shown in Fig. 6. The inboard radial build is optimized such that it satisfies the neutron shielding criteria of superconducting magnet and reactor configuration. Clearly the dose rate at one day after the reactor shutdown is less than 1000 R/h, the highest dose rate occurring at the low temperature radiation shield made of titanium hydride. Therefore, the utilization of remote maintenance machine using semiconductors is not limited.

After cooling of 50 years, 97% by volume of the radwastes of DREAM reactor is classified into low level wastes, if nitrogen impurities of SiC/SiC composites were reduced below 2 wppm.

The main energy source that could cause the accidental release of radioactive materials is the afterheat in the blanket. The temperature rise of the first wall by afterheat of 1.4 full power operation in case of a loss of coolant accident was roughly evaluated. The flow loss was assumed to be 100% and cooling of the first wall occurs by only thermal radiation. The temperature rise is below 40°C and the integrity of the first wall is not damaged. The blanket is replaced every 2 years in the shortest case. The availability of the DREAM reactor is assumed to be 70%. So, 1.4 full power operation was used in this evaluation. However, the afterheat is mainly controlled by the short life radionuclide and saturated in this operation period. So, the temperature rise in the first wall is nearly the same even in longer operation.

8. Conclusions

JAERI studied a concept of a commercial fusion power reactor (5.5 GW, electric output: 2.7 GW) having high environmental safety, high thermal efficiency and high availability. The gross reactor configuration was designed to achieve good maintainability, high performance breeding blanket, high efficiency power generation system. The design was based on the use of low activation structural material (SiC/SiC Composites) and helium as a coolant.

1. Easy maintenance was attained by the replacement method of each sector and the radiation environment was less than 10^3 R/h in the reactor chamber.
2. The net thermal efficiency over 45% was attained by high temperature helium gas Brayton cycle.
3. Most of the radwastes of the DREAM reactor can be disposed in shallow land burial as a low level radwaste after cooling for several tens of years.

The realization of this reactor concept greatly depends on the success of development of high performance SiC/SiC composites.

Acknowledgements

The authors would like to thank Dr. Ohta, Director of Department of Fusion Engineering Research and Dr. T. Nagashima, Deputy Director of Department of Fusion Engineering Research, Japan Atomic Energy Research Institute for their support for this work.

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