FUSION BLANKETS FOR CATALYZED D-D AND D-He^3 REACTORS

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Summary

Blanket designs are presented for catalyzed D-D (Cat-D) and D-He^3 fusion reactors. Because of relatively low neutron wall loads and the flexibility due to non-tritium breeding, blankets potentially should operate for reactor life-times of ~30 years. Unscheduled replacement of failed blanket modules should be relatively rapid, due to very low residual activity, by operators working either through access ports in the shield (option 1) or directly in the plasma chamber (option 2).

Cat-D blanket designs are presented for high (~30%) and low (~12%) β non-circular Tokamak reactors. The blankets are thick graphite screens, operating at high temperature to anneal radiation damage; the deposited neutron and gamma energy is thermally radiated along internal cavities and conducted to a bank of internal SiC coolant tubes (~4 cm. ID) containing high pressure helium.

In the D-He^3 Tokamak reactor design, the blanket consists of multiple layers (e.g., three) of thin (~10 cm.) high strength aluminum (e.g., SAP), modular plates, cooled by organic terphenyl coolant.

Introduction

Blanket designs have been developed for catalyzed D-D [Cat-D] and D-He^3 fusion reactors. Because of low neutron wall loads [for DHe^3 reactors] and the elimination of tritium breeding blankets have the potential to operate for reactor lifetimes of ~30 years and without having to be replaced on a routine basis. Further, unscheduled replacement of failed blanket modules appears unlikely because of redundancy and good neutron damage resistance. If replacement of some modules is required, this can be done relatively rapidly, due to very low residual activity, by operators working either through access ports in the shield [option 1 (Fig. 1)] or directly in the plasma chamber [option 2].

The use of advanced fuels has a number of important potential benefits for fusion reactor blankets:

. Minimum radiation damage - either because of very low neutron wall loads [i.e., in the DHe^3 reactor] or ability to use non-breeding graphite blankets, which should anneal at high temperatures [i.e., in the Cat-D reactors].

. Elimination of the need to replace blanket modules during the life of the reactor at least on a scheduled basis - non-scheduled replacement of modules due to unexpected failure may be necessary .

. Ability to effectively use low activity materials such as aluminum, SiC, and graphite which minimize activity and personnel dose rates in the reactor, and virtually eliminate radwaste handling and storage problems.

. Rapid replacement of failed blanket modules with essentially no remote handling.

. High plant availability associated with minimum need for shutdown for blanket maintenance and replacement.

. Low blanket cost.

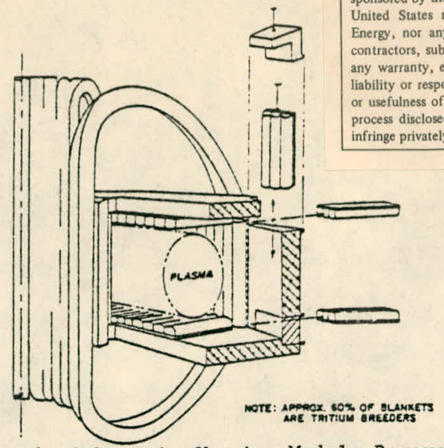

Fig. 1 Schematic Showing Module Removal

. No use of scarce resources [Be, Cr, etc.] in blanket.

. Elimination of the tritium processing circuits in the blanket system.

. Elimination of tritium leak paths to the environment from the blanket and power conversion systems.

. Elimination of the need for tritium storage.

Catalyzed D-D Blanket Designs

Cat-D blankets have been designed for high [~30%] and low [~12%] β noncircular Tokamak reactors. The blankets are thick graphite screens, [Fig. 2] operating at high temperature to anneal radiation damage; the deposited neutron and gamma energy is thermally radiated

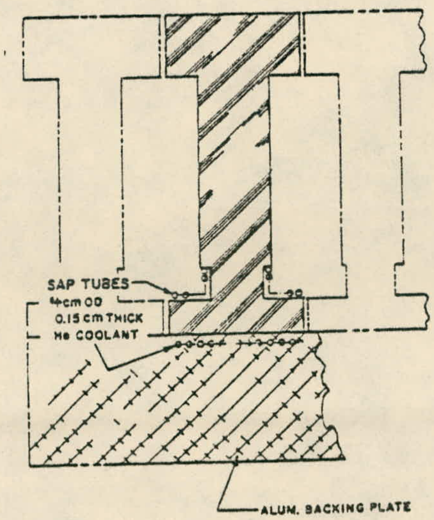

Fig. 2 GRAPHITE BLANKET MODULE

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along internal cavities and conducted to a bank of internal SiC coolant tubes [~4 cm. ID] containing high pressure helium. In option 1 the graphite blocks are mounted on heavy Al backing plates [cooled by He], which are supported from the fixed shield. The shield also provides the primary vacuum seal. In option 2 the graphite blocks radiate to a set of coolant tubes fixed to a separate backing plate which is also supported from the fixed shield. Non-neutron energy, i.e., bremsstrahlung, is transmitted almost completely through a thin, low thermal conductivity, low density graphite layer [either graphite felt or cloth] into the high temperature bulk graphite blocks. Designs based on bulk graphite surfaces have also been examined.

Typical blanket sizes and weights for the Cat-D designs [option 1] are as follows: high β - The vertical inner and outer walls are ~13 m long; each outer module is 1.5 m wide x 13 m x 1 m thick and holds 5 graphite blocks. The blocks are 30 cm wide x 13 m x 84 cm thick [with a .16 m thick Al plate] and have a total module weight of ~35 Mt. Inboard modules are essentially the same. The maximum lengths of the top and bottom modules are ~8 m. Because of their tapered width, the weights of the top and bottom modules will be less than either the inner or outer modules. There are approximately 18,000 coolant tubes in the reactor, with 20 tubes for each graphite block.

Low β - The vertical inner and outer walls are ~26 m long. To facilitate handling and fabrication, two blanket modules are vertically stacked to form the side wall. The outer modules are similar to those for the high β design, but are somewhat larger, i.e, there are 7 blocks/module. Each block is 30 cm wide x 13 m x 84cm thick, and the module is 2.1 m wide. The maximum lengths of the top and bottom modules are 10 m. There are approximately 35,000 coolant tubes in the reactor with 20 tubes for each graphite block. There are ~200 modules in the reactor for both designs.

The Cat-D, high β design has a gross wall loading of 1.11 MW(th)/m^2 [bremsstrahlung and neutron blanket wall loading is 0.76 MW(th)/m^2 and the balance appears in the divertor]. Steady state blanket temperatures are calculated by the computer code, CONRAD,[1] using neutron and gamma heating distributions calculated by a 1-D group P_3S_8 ANISN model. The effect of helium coolant outlet temperature from the SiC tubes is investigated for values of 800°C, 900°C, and 1000°C, with the inlet temperature fixed at 400°C. The effect of the number of coolant tubes in the graphite block is investigated so as to determine the effects on heat pickup and maximum blanket temperature. The range examined is from 16 to 24 tubes. The effect of He outlet temperature in the Al backing plate is also examined for the range of 300 to 400°C.

The maximum graphite first wall surface temperature is found to be ≤ 1800°C for all cases investigated. This temperature is well below the maximum allowable temperature of ~2000°C established by graphite evaporation. Depending on coolant tube design, maximum helium coolant velocities range from 16 m/sec to 32 m/sec, well within HTGR technology. The helium pumping power ratio [pumping power/heat pickup] is low, ranging from 0.5 to 1.0%.

For the Cat-D, low β design, the gross wall loading is 2.03 MW(th)/m^2 [bremsstrahlung and neutron blanket wall loading = 1.37 MW(th)/m^2, the balance appears in the divertor]. The same coolant temperatures range as in the high β design is assumed.

For the low β designs, the first wall surface temperatures exceed the design limit [~2000°C] unless a low temperature radiation sink is used. A sink equivalent in area to 5% of the total first wall is found to provide a sufficient cooling area. This implies that 5% of thermal energy is not available for high temperature heat extraction; however, this energy can be used in a power cycle operating at a source temperature of 400°C. The thermal-hydraulic characteristics for the low and high β designs are summarized in Tables I and II and it is seen that they are essentially the same.

Table I

Typical Thermal and Hydraulic Characteristics of the High β Graphite Blanket
[1.11 MW(th)/m^2 Gross Wall Loading]

	Maximum Coolant Temperature		
	800°C	900°C	1000°C
Number of Tubes/Block	20	20	20
Coolant	He	He	He
Inlet Temperature [°C]	400°C	400°C	400°C
Outlet Temperature [°C]	800°C	900°C	1000°C
Operating Pressure [atm]	60	60	60
Flow Rate [g/s]	135	108	90
Channel Velocity [m/s]	25.6	21.6	19.0
Heat Transfer Coefficient [W/cm^2°C]	0.139	0.122	0.103
Blanket Pressure Drop [psia]	2.2	1.56	1.12
Pumping Power/Thermal Power	.007	.004	.003

Table II

Typical Thermal and Hydraulic Characteristics of the Low β Graphite Blanket
[2.03 MW(th)m^2 Gross Wall Loading]

	Maximum Coolant Temperature		
	800°C	900°C	1000°C
Number of Tubes/Block	20	20	20
Coolant	He	He	He
Inlet Temperature [°C]	400°C	400°C	400°C
Outer Temperature [°C]	800°C	900°C	1000°C
Operating Pressure [atm]	60	60	60
Flow Rate [g/s]	136	109	91
Channel Velocity [m/s]	25.9	21.9	19.2
Heat Transfer Coefficient [W/cm^2C]	0.141	0.118	0.104
Blanket Pressure Drip [psia]	1.24	0.883	0.672
Pumping Power/Thermal Power	.004	.002	.001

D-He^3 Blanket Designs

In the D-He^3 Tokamak high β reactor design, the major fraction of the blanket thermal power results from plasma x-rays [E_{AV}~30KeV]. The x-rays essentially stop on the surface of the first wall, and the heat energy is conducted through the wall to a coolant system. The relatively high heat fluxes [70 w/cm^2] require that the first wall have good thermal conductivity to avoid large temperature differentials and excessive thermal stresses in the structure. Low conductivity materials such as stainless steel or titanium do not appear to be suitable. Aluminum appears to be the best choice for DHe^3 reactor blankets: it has very high thermal conductivity, low induced activity, and is plentiful and inexpensive. Since the integrated neutron wall load for the reactor lifetime [30 years] is low, no radiation damage problems are anticipated.

The blanket is formed from flat, relatively thin, aluminum sheets with internal coolant passages. Organic terphenyl coolant is preferable to helium or water, has a low operating pressure [~100 psi], low pumping power, essentially zero corrosion rate, and is stable at relatively high temperatures [~400°C] which results in good thermal cycle efficiencies [~36%]. Water would have a high operating pressure [~1000psi] but might cause corrosion problems. Thermal cycle efficiences would be limited to ~30%. Helium would have a high operating pressure [~1000 psi], high pumping power, and relatively low thermal efficiency [<30%]. The principal problem with terphenyl coolant, i.e., radiolytic decomposition by high energy neutrons and gamma rays is not of concern with DHe^3 reactors, because of the very low neutron wall loads.

The aluminum sheet blanket modules are covered with hexagonal SiC plates which are on the order of 2 cm thick. These protect the aluminum against erosion due to long-term sputtering and damage due to unexpected plasma dumps. If erosion of the SiC is excessive during the 30-year life of the blanket, the SiC plates can be regenerated in-situ by chemical vapor deposition.

The reference blanket design uses multiple layers (e.g., three) of thin [~10 cm] high strength aluminum [e.g., SAP] modular plates which operate at ~400°C and are cooled by organic terphenyl coolant [HB-40](Fig. 3). The hexagonal SiC liner elements form the first wall. Each plate, which is typically 4 m long x 1.5 m wide, has internal coolant channels [0.5 cm x 1.0 cm] arranged in two independent redundant circuits. The multiple layer, independent circuit design gives very high blanket reliability, since leaking circuits can be valved off while the reactor is operating. If the reactor operator detects impaired plasma performance caused by a leak, he can successively shut off and

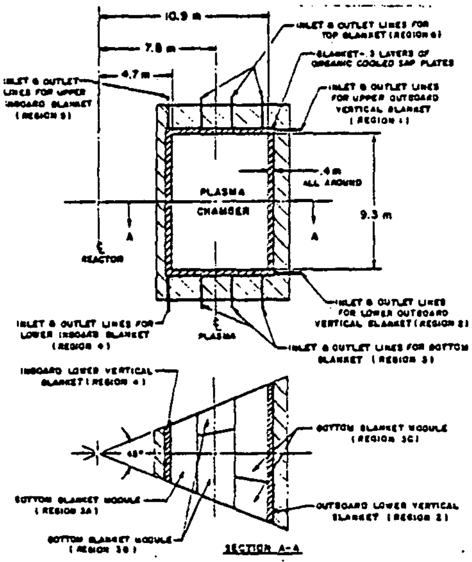

Fig. 3

switch redundant circuits until the leaking circuit is detected, without having to shut down the reactor. Calculations of temperature distributions using the two-dimensional version of the Heating-3 conduction/convection code indicate that if one coolant circuit is shut off in a given plate, the remaining circuit can take over and the rise in plate temperature will be relatively small.

The integrated neutron wall load on the aluminum blanket is only 1.0 MW(th) yr/m^2 for a 30-year plant life [80% plant factor]. The aluminum should operate for a 30-year period, in view of the low integrated neutron wall load. If both coolant circuits on a plate should fail, which seems a very unlikely event, the reactor can be shut down and failed plate can be removed from inside the plasma chamber. The procedure is discussed in a later section. Plate replacement would not be necessary since the next inner plates can then take over the load. The inner plates will operate at a lower temperature [e.g., 50 - 100°C lower] than the plate facing the plasma. Since the thermal load of the inner plates is very small compared to the outer plate, the thermal power conversion efficiency is not significantly affected. The lower temperature should result in lower failure and pyrolytic decomposition rates.

A study has been made of the effect of various blanket parameters on blanket performance. The parameters studied include coolant velocity, coolant passage shape, nature of surface [fined vs. smooth], coolant passage size, module length, and module width. The optimum dimensions for a blanket module depend on its position in the reactor [Fig. 4]. Table III gives the dimensions and weights for the first layer of blanket modules. Region 1 and 2 are the top and bottom halves of the outboard blanket, regions 3A, 3B, and 3C comprise the top part of the blanket, regions 6A, 6B, and 6C comprise the bottom part of the blanket, and regions 4 and 5 are the top and bottom halves of the inboard blanket. The maximum module weight is less than three metric tons, and replacement of a failed module should not be difficult.

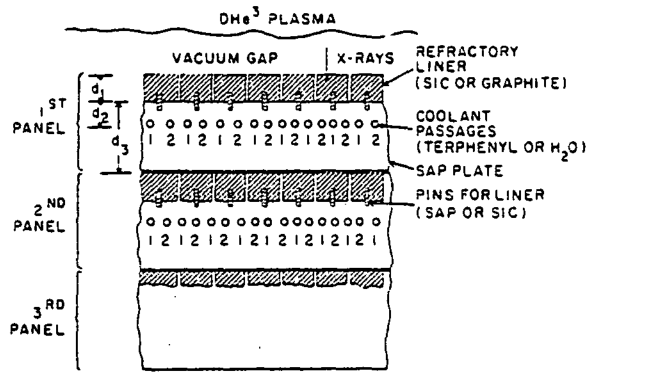

Fig. 4 ALUMINUM BLANKETS FOR DHe^3 REACTORS CROSS SECTION

Thermal-hydraulic parameters for a typical module are: coolant velocity, 8 m/sec; ΔP, 3 atm; inlet and outlet temperatures, 350 and 375°C; film temperature drop, 20°C; and pumping power/thermal power extraction ratio, 0.4%.

The thermal-hydraulic parameters are calculated for smooth rectangular coolant passages [0.5 x 1.0 cm] in the aluminum plate. Of the four cases studied [smooth circular holes, smooth rectangular holes, finned circular holes, and finned rectangular holes] the smooth rectangular holes were preferable. Table IV compares thermal hydraulic parameters for the four types of coolant passages at the optimum coolant velocity for each. Although the typical parameters given in Table IV are attractive and practical, a more optimized design with some change in coolant passage dimensions is probably achievable, and this would likely involve a reduction in both film and coolant transport [inlet to outlet] temperature differences. ΔP and $(R)^{-1}$ [pumping power to thermal extraction power ratio] would probably increase somewhat. Values for organic properties have been taken from the extensive work on organic cooled CANDU reactors.[2]

Table III

Organic Cooled Blanket Module and Characteristics for DHe^3 Reactor

[First Layer of Modules]

Region	Module Length, m	Module Width, m	# of Modules in Reactor	Module Weight, kg
1	4.62	1.60	36	2595
2	4.62	1.60	36	2595
3A	3.70	2.04	8	2650
3B	4.06	2.04	12	2907
3C	3.86	2.04	16	2764
4	4.62	1.21	24	1962
5	4.62	1.21	24	1962
6A	3.70	2.04	8	2650
6B	4.06	2.04	12	2907
6C	3.86	2.04	16	2764
Total:			192	

Note:
- Modules have the same construction in the following regions: 1 and 2; 3A and 6A; 3B and 6B; 3C and 6C; 4 and 5. Thus five different kinds of modules must be fabricated.
- There is a 2 cm gap between modules for ease in removal.
- Average density of 2.7 for module; thickness of 13 centimeter.

Table IV

Thermal-Hydraulic Parameters for DHe^3 Reactors

[HB-40 Terphenyl Coolant]

Design Parameter	Smooth Circular Holes	Finned Circular Holes	Smooth Rec-tangular Holes	Smooth Rec-tangular Holes
Coolant Passage Size, cm	0.75	0.75	0.5x1.0	0.5x1.0
Coolant Velocity, m/sec	12.0	11.0	8.0	8.0
ΔP for Module, atm [4 meter length]	5.2	12	3	6.4
Film Temperature Drop, °C	30	14	20	8
ΔT for Module, °C [4 meter length]	32	36	25	28
Pumping Power/Thermal Power	0.0067	0.014	0.004	0.011

Because of the low neutron wall loading [0.04 MW (th)/m^2], the radiolytic organic decomposition rate is quite small. For a 2 GW(th) $D\text{-}He^3$ reactor [1 GW(e)] the total organic decomposition rate is ∿240 kg/hour based on HB-40 decomposition rate data.[2]

Approximately one-half of the decomposition results from radiolytic effects [neutrons and gammas], with the remainder due to pyrolysis. Neutron and gamma energy deposition in the HB-40 coolant is calculated using a 1-D P_3S_8 ANISN model [100 group] with ENDF/B-IV cross sections. At $2.00/kg for HB-40, organic makeup costs are low, ∿0.5 mills/KWH.

References

1. J. A. Fillo, et al., "CONRAD: Heat Conduction-Radiation Code - Part I," BNL Report 50504 (1976).

2. J. L. Smee, et al., "Organic Coolant Summary Report," AECL 4922 (1975).