SUMMARY

THERMAL DESIGN AND ANALYSIS OF
STEADY STATE GRAPHITE BLANKETS

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1. Introduction

In all fusion reactors using the deuterium-tritium fuel cycle, a large fraction (~80%) of the fusion energy will be released as ~14 MeV neutrons. These neutrons must be slowed down in a relatively thick blanket surrounding the plasma, and their kinetic energy converted to high temperature heat. This heat may be continuously removed from the blanket by a coolant system.

The fast 14 MeV neutrons seriously activate many candidate blanket materials. Moreover, the radiation damage resulting from these fast neutrons, i.e., radiation-induced embrittlement and swelling, is a serious problem and may necessitate frequent replacement of the blanket. Thus it is desirable that the blanket be made from materials that exhibit little or no residual radioactivity. This not only greatly eases repair, maintenance, and replacement operations, but also greatly reduces the radioactivity of damaged materials that must be handled and stored.

In several recent studies, notably Conn, et al.,⁽¹⁾ Powell and Lazareth⁽²⁾ and Powell, et.al.⁽³⁾, the use of graphite as a moderating and protective material for fusion reactor blankets has been considered. These studies indicate that thick layers of graphite in front of coolant surfaces are attractive since radiation damage to coolant surfaces can be considerably reduced. The graphite layer exhibits very low residual radioactivity, low Z, and very high temperature capability. In addition radiation damage to the graphite should anneal out.

In the present study we consider the design aspects and analysis of a steady-state graphite blanket. The approach is somewhat analogous to the ISSEC concept⁽¹⁾, but can operate at substantially higher first wall loads.

2. Description of Graphite Blanket Design

A typical design configuration is shown in Fig. (1) for either an experimental power reactor (EPR) or commercial reactor. The primary blanket is a thick screen of graphite blocks in which the fast neutrons and gammas deposit most of their energy. The bremsstrahlung energy is deposited on the graphite surface and re-radiated away as thermal radiation. Almost all of neutron and gamma deposited energy thermally radiates down cavities between the blocks to the secondary blanket where it is absorbed by a row of SAP tubes cooled by high pressure helium. The coolant tubes are protected by

the primary blanket from radiation damage and should not require replacement during the life of an EPR or commercial reactor.

Graphite surface temperatures (T_s) should not exceed 2000°C since surface evaporation at higher temperatures would poison the plasma. To operate at high first wall loads and not exceed the allowable surface temperature, the new concept employs graphite blocks which have a thin ($\sim 0.5 - 1\text{cm}$) surface layer of low conductivity material (e.g., graphite fibrous mat or pyrographite). The surface is radiatively cooled by a small portion (10-20%) of the blanket surface acting as a radiation sink. The sink is a simple tube bank of conventional material, such as SAP tubes, and cooled by helium. Replacement of the sink may or may not be necessary during the life of the EPR. Assuming the life of a commercial reactor to be 30 years, the sink would have to be replaced. In either case replacement could be done much faster and cheaper than if the entire blanket were conventional.

3. Thermal Analysis

In addition to surface temperatures, it is necessary to predict the steady, periodic temperatures in the interior of the blanket. While a graphite blanket has a high temperature capability, internal temperatures should not exceed $\sim 2300^{\circ}\text{C}$. In addition a knowledge of the temperature profiles is necessary for thermal stress analyses as well as the determination of heat fluxes to the coolant tubes.

For our differential system we consider a small but finite rectangular element of unit depth fixed in space. Applying the first law of thermodynamics to the system, and in the case of two solid elements in contact, relating the rate of heat-flow through an area of the element by Fourier's law, the two dimensional finite difference equation for non-steady heat conduction with non-uniform internal neutron + gamma heat-generation may be written as

$$\sum_{i=1}^4 K_{ij} (T_i - T_j) + Q_j \Delta V_j = \rho_j C_j \Delta V_j \frac{dT_j}{dt} \quad (1)$$

where

$$K_{ij} = \frac{1}{\ell_{ij}/k_{ij}A_{ij} + \ell_{ji}/k_{ji}A_{ji}} \quad (2)$$

In the present notation i represents the nodes surrounding the node of interest j . Heterogeneous, anisotropic solids are admitted in the formulation (i.e., at each node thermal properties may be temperature dependent and in addition the thermal conductivity may be orientation dependent). The interface condition for nodes surrounding the node of interest is specified by maintaining continuous thermal flu at the boundary. Coolant tubes are accounted for by adjusting the thermal conductivity in Eq. (1). For example, the heat transfer coefficient h is related to an equivalent thermal conductivity K^* , where

$$K_{ij}^* = h_{ij} l_{ij} \quad (3)$$

A radiation gap between the graphite blanket and coolant tubes is also provided for in the computer program.

For unsteady heat conduction the time derivative $\frac{dT_j}{dt}$ is made discrete by introducing the forward difference expression

$$\frac{dT_j}{dt} \approx \frac{T_j(\text{NEW}) - T_j(\text{OLD})}{\Delta t} = \frac{T_j^{n+1} - T_j^n}{\Delta t} \quad (4)$$

In addition the left hand side of Eq. (1) is assumed to be evaluated at the "old" time (i.e., at time n). This results in the standard explicit method; the temperature at time $n+1$ is an explicit function of the known temperatures and internal heat generation at time n . Eq. (1) must be modified to account for boundary conditions.

The surface which faces the plasma experiences radiative energy exchange with the surroundings. The boundary condition is expressed by

$$-k_v A \frac{\partial T}{\partial y} \bigg|_{y=0} = \sigma F \epsilon (T_s^4 - T^{*4}) A - P_o A \quad (5)$$

where F is the view factor between the element of area A and the sink area. In our case $F=1.0$ since we assume parallel planes and ϵ , an equivalent emissivity of the sink area, is taken to be $0.1 \sim 0.2$. In other words it is assumed that the sink area is 10% or 20% of the total blanket wall area. T_s is the surface temperature and T^* is the sink temperature. The plasma is assumed to be perfectly transparent to thermal radiation. Bremsstrahlung radiation from the plasma to the blanket surface is accounted for via P_o and is assumed isotropic.

Eq. (5) is introduced in an energy balance on an element which includes the surface node. This in turn couples the first node in from the surface to the surface temperature, T_s . Additional energy balances are performed to account for the internal cavity surface nodes.

Steady-state solutions are generated from arbitrary initial conditions as the asymptotic solutions of the non-steady temperature build up in the blanket. Of interest is that for a given spacing between nodes and from stability requirements, the effect of the low conductivity surface layer is to increase the time-step over that of the internal nodes. Hence, the time-step for the numerical calculations is dictated by the internal nodes. The computer program is written entirely in FORTRAN IV and consists of four principle routines to handle data input, radiant view factor determination, step-by-step solutions of the heat balance of all nodal points, and print-out of final results.

4. Graphite Blanket Test Cases

Tables I and II provide summaries of the blanket materials, material properties as well as parameters studied in the test cases. Figs. (2) and (3) are plots of the neutron + gamma heat-deposition rates per unit volume for total wall loadings of 1 MW(th)/m². Wall loading, as used here, refers to thermal fusion power divided by the surface area of the torus, the reactor area which faces the plasma. That is, we assume as Tokamak device. The results in Fig. (2) are for a commercial reactor. The steep rise in the curve at 45 cm reflects the presence of LiAlO₂ for tritium breeding. In contrast, Fig. (3) are the results for a non-tritium breeding experimental power reactor.

With regards to the heating calculations, the neutron and gamma ray fluxes are found from a solution to the one-dimensional, linear Boltzmann transport equation with general anisotropic scattering. The geometry of the reactor is represented as an infinite cylinder with a vacuum boundary condition at the outer radius. Knowing the fluxes, kerma factors (kinetic energy released in the blanket materials), number densities of the constituent materials and the geometry of the blanket, the heat deposition rates can be calculated.

Case I is a circular plasma, experimental power reactor with no tritium breeding, 17 W/cm² bremsstrahlung load (P_0), a plasma on time of 30 sec and off time of 30 sec. Three surface layer materials are considered:

a) 1-cm graphite layer; b) a 1-cm pyrographite surface layer; and c) a $\frac{1}{2}$ -cm fibrous mat. The sink cooling tubes as well as cooling tubes internal to the blanket are made of sintered aluminum product (SAP), 1 cm O.D, 0.15 cm thick, with operating temperature = 400°C. With all three surface layer materials, the maximum surface temperature $[(T_s)_{\max}]$ is well below the design limit of 2000°C for both 10 and 20% sink area variations. Fig. (4) is a plot of T_s for 1.0 MW/m² wall loading. Of significance is the fact that a 1-cm graphite layer results in a small ΔT_s change over an operating cycle (plasma on and off). From the standpoint of cyclic thermal stresses, this is advantageous in addition to the fact that the blanket is of uniform graphite material. This reduces having to mate two different graphite materials. Maximum internal temperatures just below the surface layer are ~1800°C. Internal temperatures deeper in the blanket are considerably lower.

Case 2 is a non-circular plasma, experimental power reactor with no tritium breeding, 17 W/cm² bremsstrahlung load, a plasma on time of 30 sec and off time = to 30 sec. Compared with the circular plasma design, the non-circular design results in a thinner blanket. In addition more heat (17% compared with 10% in the circular case) is deposited in the Al backing plate attached to the blanket. Both cases require cooling of the backing plate.

As in the circular design case, the maximum surface temperature can be maintained below the 2000°C design limit for all surface layer materials as well as percentages of sink area. Fig. (5) is a plot of the surface temperature for a 1-cm pyrographite layer, wall loading = 1 MW/m². In essence the same conclusions hold for the non-circular blanket design as in the circular.

Case 3 is a commercial power reactor with tritium breeding. (LiAlO₂) is the breeding material.) Two surface layer materials are considered: a) a 1-cm pyrographite surface layer, and b) a $\frac{1}{2}$ -cm fibrous mat, as well as three cooling tube materials: SAP at 400°C, V at 800°C, and SiC at 1000°C. With a plasma on time of 30 sec, plasma off 30 sec $(T_s)_{\max}$ increases with wall loading, the maximum occurring at 3 MW(th)/m² $\approx$ 1970°C. For 1 and 2 MW(th)/m² wall loadings, the sink area was set equal to 20% while for the 3 MW(th)/m² case, the sink area was 30% to keep within the surface temperature limit. For Case 3 the fibrous mat decreased $(T_s)_{\max}$ as compared to the pyrographite layer by $\approx$ 40 to 80°C, the largest difference occurring at the highest wall loading. Increasing the cooling tube temperatures shifted $(T_s)_{\max}$ higher but it still was within the design limit. The difference in $(T_s)_{\min}$ between the two surface layers was

~100-180°C, depending on cooling tube temperature and wall loading. In all cases the LiAlO_2 ceramic temperature was below the melting point of 1900°C.

For a plasma on time of 105 sec and plasma off of 30 sec, the same general trends were found as for the shorter on time but $(T_s)_{\text{max}}$ was larger. Internal temperatures tend to run hotter as well. For the 3 MW(th)/m² wall loading the 2000°C surface temperature limit was exceeded with the pyrographite surface layer but not with the fibrous mat.

Conclusion

In summary insofar as thermal aspects are concerned, the graphite blanket concept as presented here appear most promising for both experimental as well as commercial reactors. In particular the introduction of a low conductivity surface layer permits us to go to higher first wall loadings for commercial reactors. This has significant implications for commercial reactor costs since high first wall loadings imply the possible construction of smaller reactors (size-wise) but with the same thermal fusion power output of larger reactors.

References

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Table I: Material, and Thermal Properties

	K_h W/cm ² °C	K_v W/cm°°C	ρ g/cm ³	C cal/g°°C
Graphite	0.5	0.5	1.9	0.5
Pyrographite	1.0	0.01	1.9	0.5
Graphite Fibrous Mat	0.003	0.003	1.9	0.5

Table II: Geometry and Physical Parameters

Case	Surface Layer	Geometry				Wall Loading WL, MW(th)/m ²	Effective Sink Area %
		D ₁ , cm	D ₂ , cm	L ₁ , cm	L ₂ , cm		
1	Graphite	35	10	50	10	0.5, 1	10, 20
1	Pyrographite	35	10	50	10	0.5, 1	10, 20
1	Fibrous Mat	35	10	50	10	0.5, 1	10, 20
2	Graphite	10	4	25	4	0.5, 1	10, 20
2	Pyrographite	10	4	25	4	0.5, 1	10, 20
3	Pyrographite	50	10	74	10	1,2,3	20, 30
3	Fibrous Mat	50	10	74	10	1,2,3	20, 30

(see Fig. 6)

$T^* \sim$ FIXED BOUNDARY SINK

FIG. 1

NEUTRON + GAMMA HEAT DEPOSITION RATE

$$WL = 1.0 \text{ MW/m}^2$$

DISTANCE FROM GRAPHITE SURFACE, CM

NEUTRON + GAMMA HEAT DEPOSITION RATE

CIRCULAR PLASMA

$$W_L = 1 \text{ MW/m}^2$$

EPR

— GRAPHITE SURFACE LAYER
-- PYROGRAPHITE
-·- FIBROUS MAT

COOLING TUBE: 400°C

SURFACE TEMPERATURE
PYROGRAPHITE SURFACE LAYER

$$WL = 10 \text{ MW/m}^2$$

$T^* \sim$ FIXED BOUNDARY SINK

PLASMA

FIG. 6