Conf-751125--134

LOW ACTIVITY BLANKETS FOR EXPERIMENTAL POWER REACTORS*

BNL 20717

MASTER

R. Benenati, J. Fillo, O.W. Lazareth
S. Majeski, J.R. Powell, and P. Tichler
Department of Applied Science
Brookhaven National Laboratory
Upton, New York 11973

Summary

Results of current studies aimed at the development of low activity blankets for Tokamak experimental power reactors are presented. First wall loadings in the range of 0.5 - 1.0 MW(th)/m^2 have been assumed. Blanket designs are developed for both circular plasma reactors (R=6.25m, a=2.1m) and non-circular plasma reactors (R=4.0m, a=1.0m, b=3.0m). For each of these two reactor choices, two blanket options are described. 1) In the first option, the blanket is thick graphite block structure (~50cm thickness) with SAP coolant tubes carrying helium imbedded deep within the graphite to minimize radiation damage. The neutron and gamma energy deposited in the graphite is radiated along internal slots to the coolant tubes where ~80% of the fusion energy is carred off by He at 380°C. The remaining 20% of the fusion energy is removed by a separate He stream at a slightly lower temperature. The maximum graphite surface temperature is relatively low (~1700°C at 1 MW(th)/m2). 2) In the second blanket option, the blanket is composed of aluminum modules. The aluminum shell (5000 series alloy) is maintained at a low temperature (~200°C) by a water coolant stream. Approximately 40% of the fusion energy is removed in this circuit. The remaining 60% of the fusion energy is deposited in a thermally insulated hot interior (SiC and B_4C) where it is transferred to a separate He coolant, with exit temperature of 700°C.

In each of the four blanket designs described, a modular blanket approach is adopted, with a fixed continuous shield supporting the modules. The inner wall of the shield forms the primary vacuum seal. Modules can be inserted and/or removed through a set of 36 access ports in the shield; module-header connections are made in the access ports after insertion. The complete blanket is formed by the assembly of ~200 modules. Replacement of all modules in the blanket is estimated to require several weeks.

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 which must be slowed down in a relatively thick blanket surrounding the plasma, thereby converting their kinetic energy to high temperature heat which can be continuously removed by a coolant stream and converted in part to electricity in a conventional power turbine.

These fast neutrons activate many candidate blanket materials and induce radiation damage which may necessitate frequent replacement of the blanket. It is desirable therefore that the blanket be made from materials that exhibit little or no residual radioactivity thereby easing the problems associated with repair, maintenance, replacement and storage of blanket components. This paper describes two different low activity blanket concepts currently under study at Brookhaven National Laboratory which appear to have merit for experimental power reactors.

Overall Mechanical Design

To provide a basis for current studies, two Tokamak EPR designs were selected, namely, the circular plasma reactor corresponding to the ANL-TEPR design[1] and the non-circular plasma reactor corresponding to the GA EPR design,[2] overall dimensions of which are shown in Fig. 1. For each of these two reactors, two different blanket concepts have been analyzed, one based on the concept of a thick graphite wall and all helium coolant system and the other composed of aluminum shell modules cooled by water and helium. In both concepts, the overall mechanical design is roughly as shown in Fig. 2 thru 4.

Since at this point in the development of fusion reactor technology, it is impossible to speak with assurance of the useful life of components, we have elected to design the blanket in a modular fashion so that should replacement of any modules be required, it could be accomplished with reasonable effort.

Fig. 2 shows schematically how the blanket and shield is constructed. The shield forms a fixed structure from which the blanket modules are supported and also provides the primary vacuum seal. Blanket modules are mounted on heavy aluminum backing plates which are in turn supported from the fixed shield. Fig. 3, a representative 20° sector of the torus, shows three vertical outer modules and one vertical inner module. Not shown are the tapered upper and lower horizontal modules which complete the blanket region. The complete blanket consists of 72 vertical modules and 108 horizontal modules arranged so that any one of the 10 modules associated with each 20° sector can be removed through relatively small access ports located on the outer wall between adjacent magnets (see Fig. 4). The upper and lower access ports are so arranged as to permit removal of any one or more of the modules associated with each sector. For example, removing the upper L-shaped plug permits removal of the upper horizontal modules or the outer vertical modules, while the lower plug provides access to the lower horizontal modules. The inner vertical modules would be moved to the outer wall (via manipulators inserted horizontally thru both the upper and lower openings) after which they can be removed vertically thru the upper opening. Alternately, the inner vertical modules might be replaced by solid graphite modules (such as are described later) thereby eleminating the likelihood of their ever requiring replacement while at the same time imposing a slightly larger heat load on the remaining aluminum modules which are relatively much easier to replace.

The non-circular plasma case is similar with suitable dimensional changes as indicated later.

* Work performed under the auspices of the U.S. Energy Research and Development Administration.

EB

Blanket Design

The two alternate blanket module designs being studied consist of an all graphite module as shown in Fig. 5 and an aluminum jacket module as shown in Fig. 6.

In several recent studies, notably Conn, et al,[3] Powell and Lazareth,[4] and Powell, et al.[5] 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. The graphite blanket module shown in Fig. 5 consists of 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.

The aluminum jacket module shown in Fig. 6 is fundamentally different, consisting of a water cooled aluminum can filled with silicon carbide and boron carbide both of which are cooled by direct contact with helium gas. Each aluminum shell with its elliptical head facing the plasma is designed to contain the helium coolant at 20 atms pressure, while the shell itself is cooled to approximately 200°C by integral water carrying passages. Immediately behind the elliptical head and extending for approximately 20 cm is a region of silicon carbide blocks in which much of the neutron moderation takes place. Behind the SiC blocks, there is 30 cm of B_4C in which the remainder of the neutron slowing down and absorption occurs. Thus the bulk of the fusion energy is absorbed by these high temperature ceramic materials from whence it is transferred to the helium stream at temperatures of the order of 700-800°C.

Both the graphite modules and the aluminum jacket modules are mounted on 20 cm thick aluminum plates which form the basic support for the modules. Since a significant portion of the plasma energy penetrates to this aluminum plate, internal coolant passages are provided.

Neutronics

Each blanket module was subdivided into a number of zones and within each zone, the components were homogenized for the one dimensional ANISN[6] calculations. The geometry of the reactor is represented as an infinite cyclinder (with its axis in the center of the plasma) with a vacuum boundary condition at the outer radius. A P_3 option was used for the order of angular scattering and an S_8 option for angular quadrature. The 14.1 MeV source neutrons are taken to have a uniform spatial distribution in the plasma region. The coupled neutron and gamma-ray cross sections (for 100 neutron energy groups and 21 gamma-ray energy groups) together with the neutron and gamma-ray kerma factors are supplied by the data library DLC-37.[2,7]

The cylindrical geometry used in the calculations approximated the actual geometry of the reactor designs by equating the cross sectional areas of corresponding zones in the cylindrical and actual geometries. The wall loading was 1.0 megawatts (thermal)/m^2. The compositions, volume fractions and dimentions of each zone for each of the four designs are given in Table I.*

The total neutron fluxes are shown in Fig. 7. On each curve there is indicated the boundary between the blanket module and its thick aluminum backing plate as well as the boundary between the aluminum backing plate and the shield. Fig. 8 shows the total heat deposition rates due to neutron and gamma heating as a function of distance from the first wall. The sudden rise in the heat deposition rate in the aluminum modules at about 20 cm is a consequence of the B_4C which starts at this point. The neutron energy escaping from the shield is about 10 eV/fusion neutron for the circular aluminum case, about 50 eV for the circular and noncircular graphite cases, and about 50 eV for the noncircular aluminum case.

Thermal and Hydraulic Analysis

Graphite Modules

Since the graphite modules represent a rather unusual design, detailed thermal analysis was undertaken to determine maximum surface temperatures, to predict the steady, periodic temperatures within the structure, and to determine the heat flux to the internal coolant tubes deep within the structure.

To insure that the graphite surface temperature did not exceed 2000°C, since surface evaporation at higher temperatures could poison the plasma, we have provided a thermal radiation sink covering from 10-20% of the first wall. We have also examined the use of special surface layers of low conductivity material such as fibrous mats or pyrographite. The radiation 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.

In our thermal analysis, we have considered a small finite rectangular element of unit depth, for which the two dimensional finite difference equations for non-steady heat conduction with non-uniform heat generation may be written as:

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

where

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

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 flux at the boundary. Coolant tubes are accounted for by adjusting the thermal conductivity in Eq. (1). For example, the heat transfer coefficient, h, may be related to an equivalent thermal conductivity, k*, by

$$k^* = h\ell$$

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.

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

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 temperature, and internal heat generation at time n.

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

$$-kA \left.\frac{\partial T}{\partial y}\right)_{y=0} = \sigma F \epsilon \, (Ts^4 - T^{*4})A - P_o A \qquad (5)$$

where F is the view factor between the element of area A and the sink area. In the case F=1.0 since we assume parallel planes and ϵ, the emissivity of the sink area, is taken to be 0.1 ~ 0.2 (sink area of 10% or 20%), Ts is the surface temperature of the blanket, 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. Details of the use of the computer code as well as application to other geometries may be formed in a report, "CONRAD: Heat Conduction-Radiation Code" of the Brookhaven National Laboratory.

Graphite Blanket Test Cases

Table II provides summaries of the blanket materials, and material properties assumed for the test cases. Case I is a circular plasma with 17% bremsstrahlung load, a plasma on time of 30 sec and off time of 30 sec, with SAP cooling tubes operating at 400°C in both the radiation sink and the internal regions.

The dimensions of the graphite blocks, the radiation channel, the SAP coolant tubes in the graphite and the coolant tubes in the aluminum backing plate are all shown in Fig. 5 (for the circular plasma). Volumetric heating rates for all four cases are shown in Fig. 8. The various breaks in the curves of Fig. 8 reflect the changes in composition and structure as indicated in Table I. Fig. 9 shows the surface temperatures based on a plain graphite surface, a pyrographite layer, and a layer of fibrous mat. It will be noted that the change in surface temperature between plasma off and plasma on is much greater when the low conductivity surface layers are used, but for all cases studied, the maximum temperature is well below the 2000°C design limit we have assumed. Surface temperatures for the non-circular plasma cases are essentially indistinguishable from those of Fig. 9.

We have made no attempt to optimize the size of the thermal radiation sink required and can only report that a sink equal to 10% of the first wall area effectively holds the surface temperature within design limits. A 20% sink results in a slightly lower surface temperature; no sink at all results in excessive surface temperatures.

Below the surface, heat is conducted thru the graphite structure toward the region of the SAP coolant tubes. Heat is also radiated down the narrow slot to the SAP tubes. Approximately 40% of the thermal energy reaching the SAP tubes arrives via the conduction path and the remaining 60% arrives via radiation down the slot. Typical temperature profiles are as shown in Fig. 10. It should be noted that the upper line of temperatures are the graphite surface temperatures whereas all others are at the node centers. The He temperature in the SAP tubes is constant at 653°K in the lower corner of the slot. In calculating these internal temperature distributions, a radiation gap was assumed to exist between the SAP tubes and the immediately adjacent graphite structure. The graphite temperatures immediately adjacent to the SAP tubes are somewhat higher than they would have been had we assumed good thermal contact. The lowest line of temperatures in Fig. 10 represents the He coolant in the aluminum support base.

Table III indicates some of the important design parameters of the He coolant circuits associated with the graphite blanket modules. The values for radiation sink are shown parametrically to indicate that there is a rather wide range of acceptable values with much room for optimization.

Aluminum Modules

The aluminum module is fundamentally different from the graphite module in three respects: 1) the first wall being aluminum must be prevented from reaching temperatures in excess of about 250°C; 2) since the SiC and B_4C are cooled by direct contact with helium, the aluminum shell must withstand the total helium pressure; and 3) to maximize power conversion efficiency, the heat leakage from the high temperature ceramic region to the low temperature first wall coolant stream must be minimized. To accomplish these ends, it is proposed that the shell be made of material structural and corrosion properties similar to those of the 5000 series aluminum alloys, that it be water cooled, and that a 1 cm layer of low k graphite felt separate the aluminum surfaces from the SiC and B_4C. To minimize the energy fraction deposited in the low temperature region, the shell wall thickness must be kept thin, however, this then limits the internal helium pressure to rather modest levels. We have elected to use an aluminum shell 2 cm thick which then limited the He pressure to 20 atms. The shell wall is slotted on the inside with approximately 800 slots each 0.3 cm x 0.3 cm which serve as cooling water passages. Flow paths, inlet and outlet locations, and pertinent dimensions are as shown in Fig. 6.

The SiC and B_4C regions are presumed to be constructed from rectangular rods designed so as to provide a void fraction of 15% between adjacent rods forming channels for the He coolant which flows parallel to the longitudinal axis of the module in a two pass arrangement. Suitable thermal insulation must be provided between the hot carbide rods and the low temperature aluminum shell, between the hot carbide rods and water manifolds, and between the He inlet and outlet connections and the aluminum shell thru which they must pass. Each of these insulation requirements fall within current technology.

Critical stress locations are at the flat outside walls and at the junction of the elliptical head and the intermediate flat walls. It is recognized that some form of reinforcing will be required at these points to reduce stresses to acceptable levels. The hoop stress in the elliptical shell (first wall) is 4,500 psi which is about 40% of the yield stress for 5454 T-0 aluminum at 240°C. The maximum thermal stress occurs in the first wall and amounts to about 6,000 psi.

Typical thermal and hydraulic characteristics of the water and He coolant systems of the aluminum blanket module are listed in Table IV. Once again it must be emphasized that these are not necessarily optimum values. For example, we have chosen a water inlet temperature of 187°C and an exit temperature of 204°C which results in less than 0.1% of the power output required to circulate the water coolant. A larger flow rate resulting in a smaller temperature rise and the resulting higher efficiency in the power conversion cycle might well be justified.

The present design shows approximately 44% of the total energy being deposited in the water circuit with the remaining 56% going to the He circuit. This results from the EPR guidelines of no breeding or neutron multiplication and no divertor slot, all of which would change in a commerical reactor which can reasonably be expected to have a substantially larger fraction of the total energy in the high temperature circuit.

Activation Levels

The major contributors to the activation of the blanket and shield materials are Al^{26} produced by (n,2n) reactions on Al^{27}; half-life of 7.3 x 10^5 years and Na^{24} produced by (n,α) on Al^{27}; half-life of 15 hours. The values of the activation of these isotopes at reactor shut down time after a three-year period of operation are given in Table V. In ten half-lives (about five days), the Na^{24} activation is reduced by a factor of a thousand, while in ten days, it is down by a factor of one million.

Power Conversion Cycle

A suitable power conversion cycle for an EPR using aluminum blanket modules employing both water and He as coolants is shown in Fig. 11. This flow sheet represents a combination of the process conditions reported for the Summit Power Station of the Delmarva Power and Light Co.[8] (which involves a helium cooled fission reactor) and the Comanche Peak Station of the Texas Utilities Generating Co.[9] (which involves a PWR). The bulk of the helium which leaves the blanket at 1400°F is used to raise steam at 950°F and 2400° psia and to reheat the steam to 1000°F. The steam conditions are identical to those of the Delmarva Plant. They are essentially the same as the steam conditions employed in many fossil fueled power plants. The high temperature steam cycle operates at a net thermal efficiency of about 36%.

Water from the first wall cooling circuit is flashed to produce saturated steam at 370°F and 173 psia. The liquid leaving the flash drum is recycled to the first wall. The saturated steam is superheated to 500°F using some of the high temperature He. This superheated steam drives a low pressure turbine in a cycle with a net thermal efficiency of only 22.2%.

For the combined cycle, the overall efficiency is approximately 30%. It is expected that this will increase to about 32% if the fraction of total energy to the water circuit can be reduced from its present value to about 33%.

For the graphite blanket modules, the He exit temperature is only 380°C, hence, the efficiency of the high temperature portion of the power conversion cycle will be reduced substantially. On the other hand, the low pressure steam circuit with its low efficiency would be eliminated entirely and an overall efficiency in the vicinity of 30% might be realizable.

Conclusions

1. Low activity, He gas cooled blankets and shields can be incorporated into EPR's of the sizes and shapes (e.g.), ANL TEPR and GA designs) contemplated without significant penalties to performance or magnetic field requirements.

2. The total long-lived (half life ≥1 day) residual activity of such blankets is on the order of 10^6 less than that of stainless steel or niobium blankets.

3. Acceptable thermal power conversion efficiencies, i.e., 30%, can be achieved with low activity blankets.

4. Either modular aluminum and the modular graphite low activity blankets may be used for both circular and non-circular plasma EPR's.

5. For the most part, the low activity blankets use currently available materials. The modular aluminum blanket would require some modification of the basic 5000 series aluminum alloy to remove objectionable elements presently used for grain control. Suitable substitutes appear to be available. The graphite blanket requires SAP tube technology similar to that previously developed for the heavy water organic moderated reactor. No new technology would be needed, but new production facilities would be necessary.

6. The modular designs presented have the following features: small number of modules (~200 for the entire blanket) each of relatively modest total weight, rapid replacement of the entire blanket through a set of relatively small access ports on the exterior major circumference of the blanket (typically, 36 ports), and ready accessibility to the region outside the blanket and shield.

References

1. Tokamak Experimental Power Reactor Studies, ANL/CTR-75-2, June 1975.

2. Experimental Power Reactor Conceptual Design Study, GA-A13534, July 1975.

3. R.W. Conn, G.L. Kulcinski et al., "New Concepts for Controlled Fusion Reactor Blanket Design", Nucl. Technol., 26, 125 (1975).

4. J.R. Powell and O. Lazareth, "Fusion Blankets with Minimum Activation and Minimum Vulnerability to Radiation Damage", Trans. Am. Nucl. Soc., 19, 17 (1974).

5. J.R. Powell, O. Lazareth, P. Tichler, "The Pulsed Graphite Blanket Concept', Trans. Am. Nucl. Soc., 21, 50 (1975).

6. ANISN, CCC-82, Radiation Shielding Information Center, Holifield (Oak Ridge) National Laboratory, Oak Ridge, Tenn.

7. Coupled 100-Group Neutron and 21-Group Gamma-Ray Cross Sections for EPR Calculations, DLC-37, Radiation Shielding Information Center, Holifield (Oak Ridge) National Laboratory, Oak Ridge, Tenn.

8. "Summit Power Station Preliminary Safety Analysis Report", Vols. 3 & 6, Delmarva Power and Light Corp. (1974).

9. "Comanche Peak Steam Electric Stationary Preliminary Safety Analysis Report", Vol. 5, Texas Utilities Generating Co. (1974).

* The data in the Al blanket, Table I does not reflect minor design changes made subsequent to completion of the neutronics computation.

TABLE 1

BLANKET DIMENSIONS
AND COMPOSITIONS

	Aluminum Shell Blanket					Graphite Blanket				
		Circular		NonCircular			Circular		NonCircular	
Region	Material	Thickness (cm)	Volume Fraction	Thickness (cm)	Volume Fraction	Material	Thickness (cm)	Volume Fraction	Thickness (cm)	Volume Fraction
1	Plasma	210.0	1.0	169.20	1.0	Plasma	210.0	1.0	169.20	1.0
2	Vacuum	15.0	1.0	10.93	1.0	Vacuum	19.0	1.0	10.93	1.0
3	Aluminum	2.40	1.0	2.40	1.0	Graphite SAP	2.0	- 0.97	10.0	1.0 -
4	Vacuum	0.12	1.0	0.12	1.0	Graphite	10.0	1.00	10.0	0.90
5	Al_2O_3	2.62	1.0	2.62	0.90	Graphite	30.0	0.90	3.0	1.00
6	Vacuum	1.19	1.0	1.19	1.00	Graphite SAP	5.3	0.46 0.04	4.0	- [illegible]
7	Al_2O_3	0.25	1.0	0.25	1.00	Graphite SAP	1.0	0.60 0.20	1.0	1.0 -
8	SiC		0.76		0.76					
	Aluminum	16.85	0.15	5.0	0.15	Graphite	4.0	1.00		-
	Al_2O_3		0.03		0.03	Aluminum			15.0	1.0
9	B_4C		0.72		0.70					
	Aluminum	11.9	0.12	8.0	0.12	Aluminum	30.0	1.00	15.0	0.90
	Al_2O_3		0.05		0.05	Water				0.10
10	B_4C		0.55		0.55					
	Aluminum	5.5	0.12	3.5	0.12	B_4C	70.0	0.80	15.0	0.80
	Al_2O_3		0.03		0.03	Aluminum		0.20		0.20
11	Al_2O_3	0.5	1.00	0.5	1.0					
12	Vacuum	0.1	1.00	0.1	1.0					
13	Aluminum	70.0	1.00	15.0	1.0					
14	Aluminum			15.0	0.90					
	Water				0.10					
15	B_4C	70.0	0.80	15.0	0.80					
	Aluminum		0.20		0.20					

ASSUMED DENSITIES (gm/cc)

Aluminum	2.70
Al_2O_3	4.00
B_4C	2.52
Graphite	1.90
Water	1.00
SAP	2.73
SiC	3.21

TABLE II

MATERIAL AND THERMAL PROPERTIES IN GRAPHITE BLANKET

	Graphite	Pyrographite	Fibrous Mat
Heat Capacity, Cal/gm $^{\circ}$c.	0.5	0.5	0.5
Density, gm/cc	1.9	1.9	1.9
Thermal Conductivity, W/cm $^{\circ}$c Parallel to First Wall	0.5	1.0	0.003
Perpendicular to First Wall	0.5	0.01	0.003

TABLE III

THERMAL AND HYDRAULIC CHARACTERISTICS OF THE GRAPHITE BLANKET

	Helium Cooled Sink			Helium Cooled Blanket Tubes	Helium Cooled Backing Plate Tubes
	$\Delta T_f=25^oC$	$\Delta T_f=50^oC$	$\Delta T_f=75^oC$	$\Delta T_f=20^oC$	$\Delta T_f=30^oC$
T_m-°C	175	150	125	180	100
T_{ex}-°C	375	350	325	380	300
L-cm	500	500	500	500	500
D-cm	0.64	1.287	1.879	0.7	0.7
V-m/s	94.8	45.7	30.4	64.2	57
m-g/s	13.6	27.2	39.8	10.8	11.1
Re	90665	93255	95998	65342	74050
h-w/cm²°C	0.56	0.28	0.18667	0.4	0.4
ΔP-atm	2.89	0.343	0.107	1.27	1.13
n	1850	920	630	~22000	19500

TABLE IV

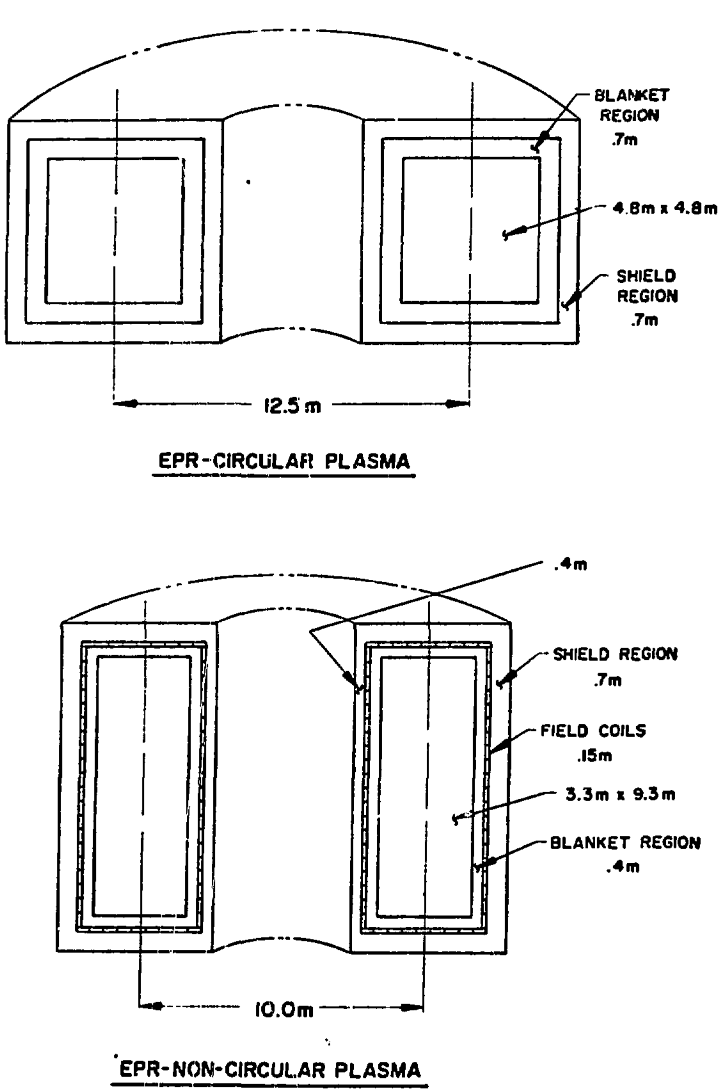
TYPICAL THERMAL AND HYDRAULIC CHARACTERISTICS OF THE ALUMINUM BLANKET

Cooling Systems (1 MW/m^2 wall loading)	
Fraction of Power to Water Circuit	0.44
Fraction of Power to He Circuit	0.56
Water Conditions	
Inlet Temperature, °C	187
Outlet Temperature, °C	204
Operating Pressure, psia	300
Water Flow Rate, gm/sec	7.33×10^6
Water Velocity, cm/sec	395
Heat Transfer Coefficient, w/cm^2 °C	3.44
Module Pressure Drop, psi	6.6
Pumping Power as Fraction of Total Power	6.5×10^{-4}
Helium Conditions	
Inlet Temperature, °C	270
Outlet Temperature, °C	730
Operating Pressure, psi	300
Helium Flow Rate, gm/sec	1.38×10^5
Helium Velocity, cm/sec	2300
Heat Transfer Coefficient, w/cm^2 °C	0.15
Module Pressure Drop, psi	7.5
Pumping Power as Fraction of Thermal Power	6.9×10^{-3}
Blanket Conditions	
Maximum First Wall Temperature, °C	239
Maximum Side Wall Temperature, °C	210
Backing Plate Temperature, °C	213
Maximum Water Film Temperature Drop, °C	11.6
Maximum Bed Temperature -B_4C Region, °C	820

TABLE V

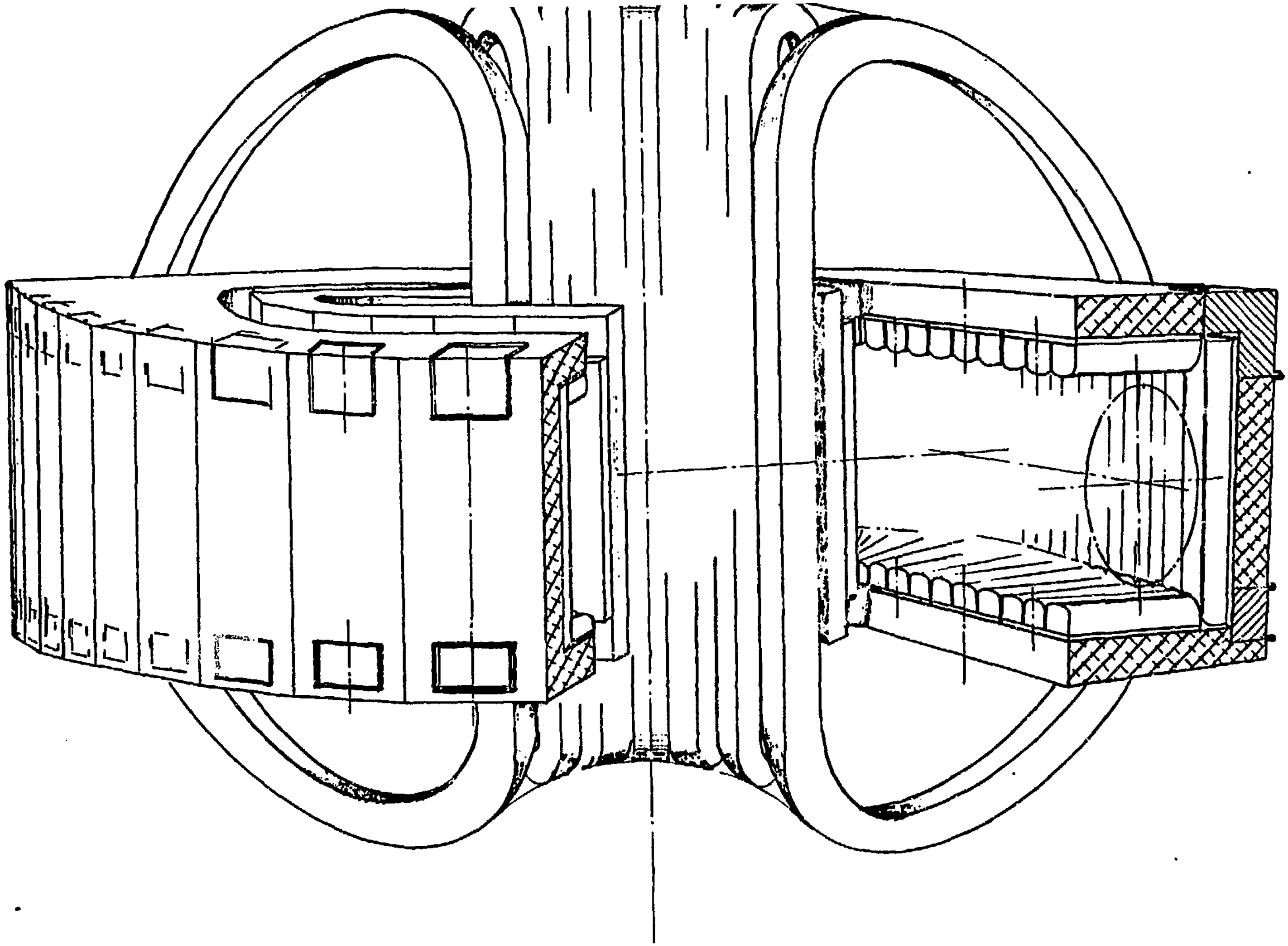
Al^{26} and Na^{24} activation (in curies) at reactor shutdown time after a three-year period of operation.

Design	Al^{26}	Na^{24}
Circular Graphite	6	1.9×10^7
Circular Aluminum	68	1.5×10^8
Non-Circular Graphite	13	4.7×10^7
Non-Circular Aluminum	91	2.1×10^8



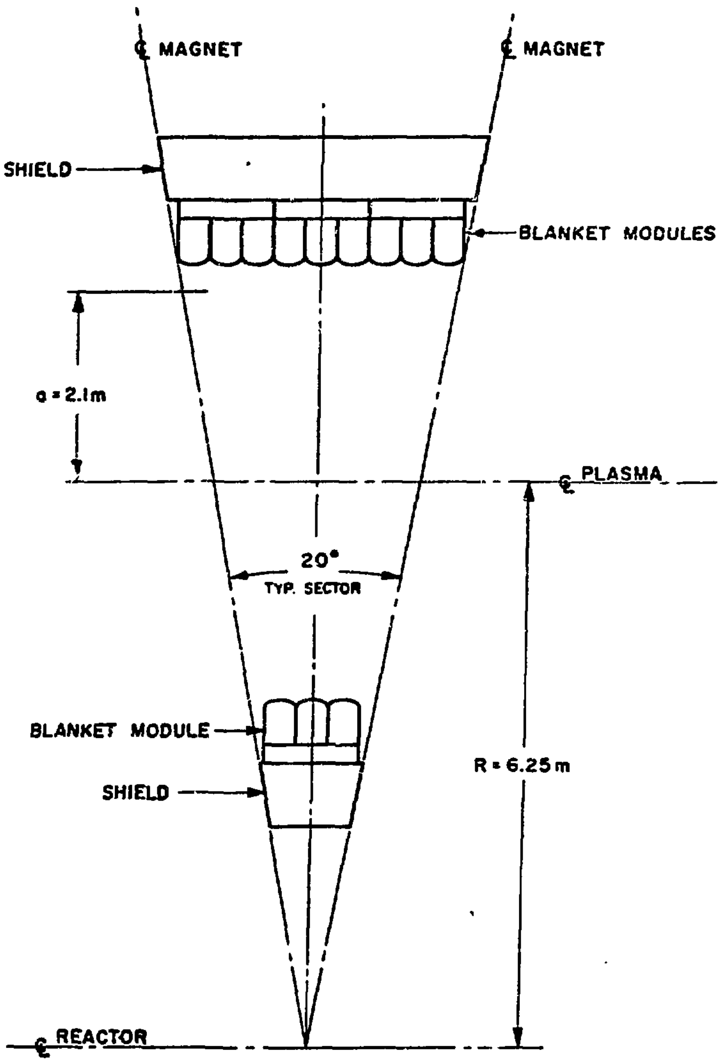
CIRCULAR AND NON-CIRCULAR PLAMAS
SHOWING TYPICAL DIMENSIONS

FIG. I



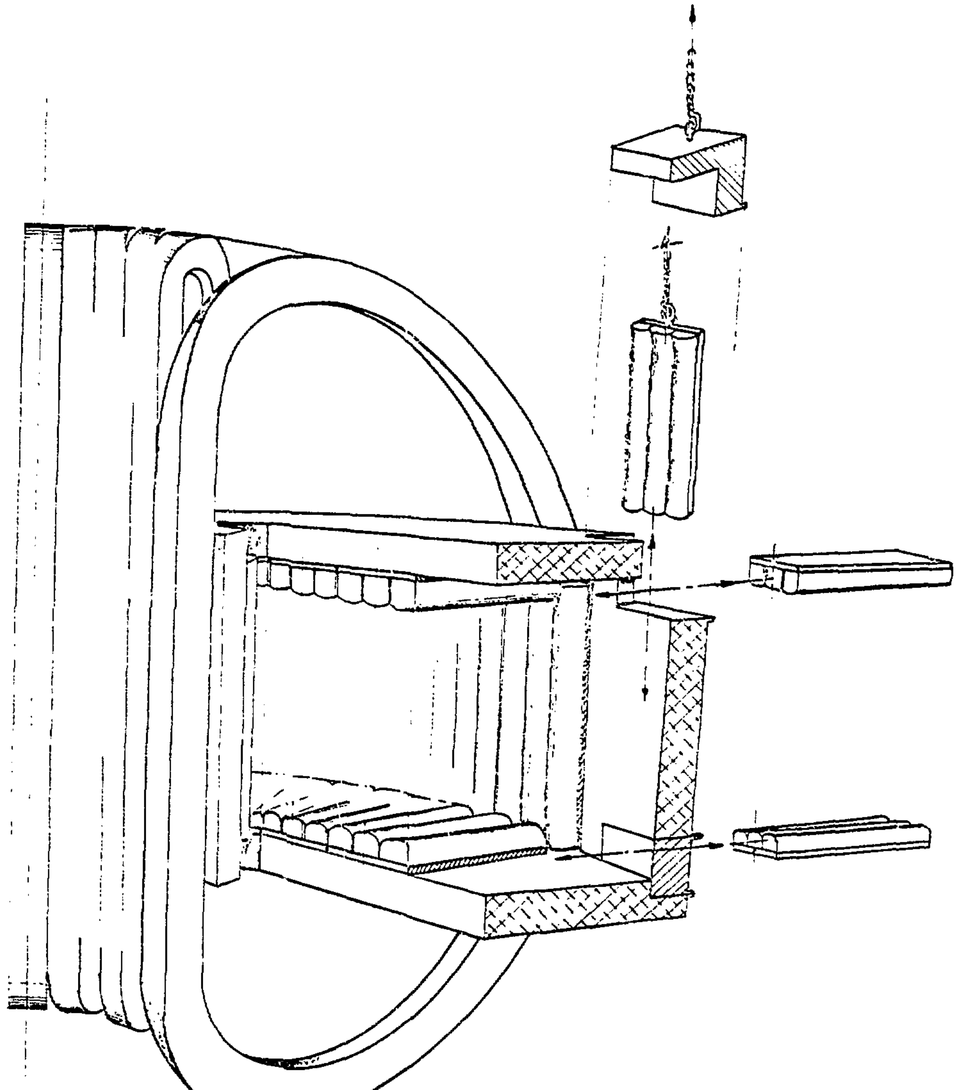
SCHEMATIC REPRESENTATION OF TOKAMAK REACTOR
SHOWING MODULAR BLANKET CONCEPT

FIG. 2



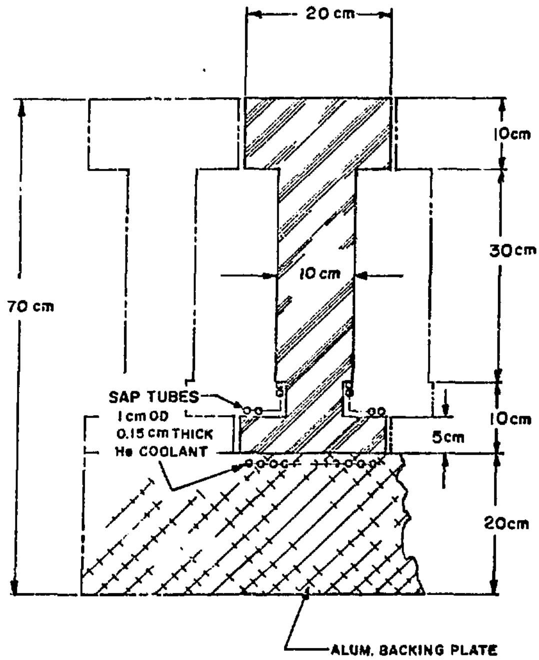
DETAIL OF 20° SECTOR OF TOROUS
SHOWING INNER & OUTER VERTICAL MODULES

FIG. 3



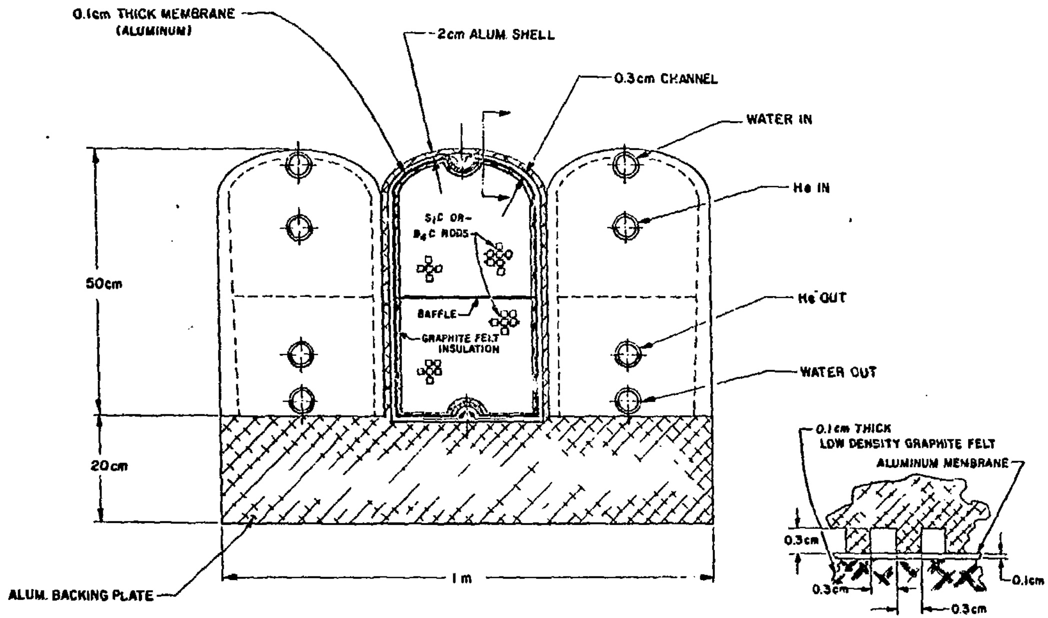
SCHEMATIC SHOWING MODULE REMOVAL

FIG.4



EPR GRAPHITE BLANKET MODULE
CIRCULAR PLASMA

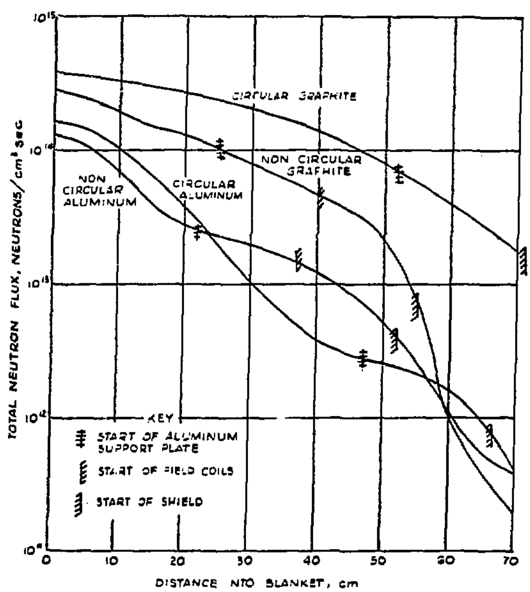
FIG. 5



SECTION

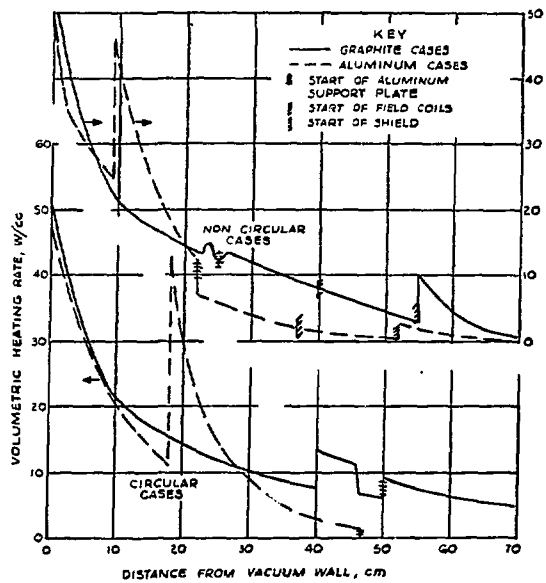
EPR ALUMINUM BLANKET MODULE
CIRCULAR PLASMA

FIG. 6



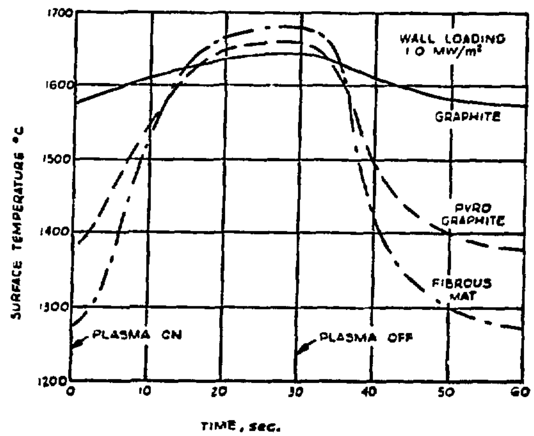
TOTAL NEUTRON FLUX vs DISTANCE

FIG.7



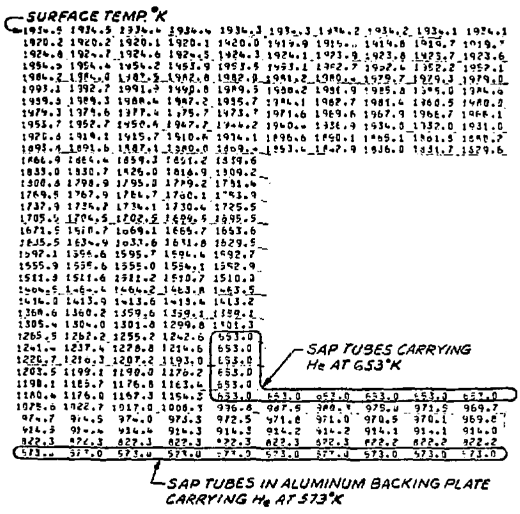
TOTAL VOLUMETRIC HEAT DEPOSITION RATES

FIG.8



GRAPHITE BLANKET MODULE SURFACE TEMPERATURE
VS. TIME FOR DIFFERENT SURFACE MATERIALS

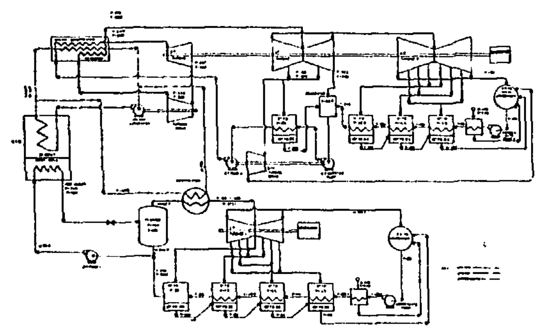
FIG. 9



WL=10 MW/m²

TEMPERATURE DISTRIBUTION IN BLANKET
RADIATION GAP - PYROG SURFACE

FIG 10



POWER CONVERSION CYCLE FOR EPR
WITH ALUMINUM BLANKET MODULE

FIG 11