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Low Activity Blanket Designs and Heat Transfer
for Experimental Power Reactors*

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by

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ABSTRACT

Two minimum activity blanket designs are described, based on the ANL TEPR circular design parameters. A first wall loading (plasma on) of 1.0 MW(th)/m^2 has been assumed. The first option is composed of SAP (sintered aluminum product) modules. The oval shaped SAP shell, in which $\sim 45\%$ of the fusion energy is removed, is maintained at a temperature of $\sim 400^\circ\text{C}$ by a He coolant stream. The remaining 55% of the fusion energy is deposited in a thermally insulated hot interior (SiC and B_4C) and removed by a separate He coolant, with exit temperature of 800°C . In the second option, the blanket is a thick graphite block structure ($\sim 50 \text{ cm}$ thickness) with SAP coolant tubes carrying He (50 atm) embedded deep within the graphite to minimize radiation damage. The neutron and gamma energy deposited in the graphite is radiated along internal slots and conducted through the graphite to the coolant tubes. To reduce surface evaporation above 2000°C , the blanket surface is radiatively cooled to a low temperature radiation sink, a bank of He cooled SAP tubes. Approximately 20% of the fusion energy is removed in this region, the remaining 80% in the primary graphite-aluminum blanket. Both blanket options are mounted on heavy Al backing plates, cooled by He, which are in turn supported from the fixed shield.

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1. INTRODUCTION

As part of the program to demonstrate commercial fusion power, ERDA has planned for the operation of a Tokamak experimental power reactor (EPR) using the deuterium-tritium (D-T) fuel cycle. This device may produce net power or simply show in principle the capability for net power. For certain the EPR will have a blanket and possibly a few blanket modules containing lithium for tritium breeding.

As a consequence of fast 14 MeV neutrons moderated in the blanket, many candidate blanket materials may be seriously activated and induced radiation damage 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 minimum activity blanket concepts, one based on SAP (sintered aluminum product) as the structural material and the other, a graphite screen protecting SAP cooling tubes, currently under study at Brookhaven National Laboratory (BNL). The present effort represents a continuation of the minimum activity concept initially proposed by Powell, et al. [1].

2. OVERALL MECHANICAL DESIGN

To place the blanket concepts in context we consider a Tokamak reactor, schematically depicted in Fig. (1). The blanket region is an octadecagon in cross section. A modular

blanket approach for both blanket designs is shown, with a fixed continuous shield supporting the modules. The inner wall of the shield forms the primary vacuum seal. Modules can be inserted and removed through a set of relatively small access ports (e.g., 36) in the shield. The complete blanket is formed by the assembly of ~200 modules. Connections between fixed headers and modules are made on the outside of the shield, as well as the vacuum seals between the fixed shield and the removable shield plugs (on the order of 1-2 m across) which cover the access ports. All connections and seals can be made by direct access.

3. ALUMINUM BLANKET-COOLING REQUIREMENTS

The first blanket option is composed of cylindrical aluminum canisters, the canister design being essentially 33 cm wide x 50 cm x 5 m long-wise with a SAP wall about 2.5 cm thick. Cooling passages carry He to hold the SAP shell temperature within the prescribed limits of $\leq 400^{\circ}\text{C}$. Typically 3 shells are mounted on a heavy aluminum backing plate to form a module Fig. (2) which in turn is attached to the shield. What the drawing does not show (but analyzed in detail by a finite element stress code) is that the outer side walls of the two outer canisters need to be reinforced by a tapered support to reduce stresses to

acceptable levels. In general the middle canister is laterally supported by adjacent canisters, but may require additional reinforcement by tapered supports in special regions. Immediately behind the insulated aluminum wall and extending for approximately 20 cm is a region of silicon carbide blocks in which most 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 coolant, separate from the shell cooling, at temperatures of the order of 700-800°C. For the ceramic materials inside the canister, no attempt is made to push them to their temperature limits but rather base the hot helium temperatures on existing HTGR technology, it being fully recognized that at some future date an optimization might indicate higher temperatures. Lastly, internal insulation to segregate the relatively cool metal shell from the substantially hotter ceramic interior parts is incorporated in the design.

We base the blanket analysis of the EPR on the following criteria: a) a plasma burn time of 30 sec on and 30 sec off; b) a wall-loading of 1 MW(th)/m² during the on cycle, resulting in an average loading of 0.5 MW/m² for the entire cycle; c) ANL-TEPR [2] circular plasma reactor dimensions (major radius = 6.25 m, minor radius = 2.1 m); and d) no tritium breeding.

Fig. (3) shows schematically the shell cooling configuration. The inlet and outlet

headers run the full length of the canister. From these headers individual coolant passages carry the shell coolant circumferentially around the canister wall. For the helium cooled shell helium is in at 200°C and out at 380°C at 40 atm pressure. The characteristic Reynolds number is such that for the He cooled shell, $Re \sim 5 \times 10^3$ to 14×10^3 while flow through the bed is laminar.

Since two coolant circuits are contemplated, i.e., one to cool the SAP canister and

the other to cool the hot interior, it is imperative to determine the total heat flow to each circuit, the neutron-gamma heating determined on the basis of the one-dimensional computer program ANISN [3].

The incident energy flux amounts to 3.5 Mev of the total 17.4 Mev deposited or 20%. This is all deposited within the first few millimeters of the first wall and is essentially a surface effect. Neutron and gamma ray heating of the first wall amounts to about 4.4 W/cc which for a 2.5 cm thick wall amounts to an additional 11%. Neutron and gamma ray heating of the side walls amounts to an additional 8.1%. Heat leakage from the hot interior region depends on the temperature levels in the canister wall and interior, the amount and quality of insulation used, and the contact area. Using 2.5 cm thick layer of graphite felt with a thermal conductivity of $0.0036 \text{ W/cm}^{\circ}\text{K}$ results in an additional heat flow of <5.5%. Thus the total heat pick up in the canister wall cooling circuit amounts to 45% of that generated by the plasma plus neutron and gamma reactions in the wall structure. The remaining 55% is absorbed in the hotter interior.

Having determined the heat pick up in the canister wall, the coolant flow can be established consistent with previously established SAP temperature limits. Optimization of the location of the wall coolant passages or of their dimensions has not been attempted. Based on an arbitrary (seemingly reasonable) choice of dimensions i.e., cooling passages 0.2 cm by 0.1 cm, 0.2 cm between center lines, the two dimensional temperature distribution in the canister wall was determined using the heat conduction code, HEATING-3 [4] from which it was determined that the maximum ΔT inside the SAP was $\sim 6^{\circ}\text{C}$ during the "plasma on" phase of the cycle. The SAP has a small heat capacity compared to its interior contents and it will probably be necessary to essentially stop the He coolant flow to the shell during the plasma off period.

The remaining 55% of the heat to be recovered from the ceramic internals represents a much easier design problem since 1) the filler material has no structural function and 2) the operating temperatures in the He circuit were established based on HTGR technology and are well below the melting points of the carbides ($>2000^{\circ}\text{C}$).

The carbide bed could be formed in a variety of shapes and sizes. What was selected for this design was a rod bundle composed of rectangular rods with spaces to provide coolant passages between the rod clusters. The hot helium flows thru the packed bed for the full length of the module, turns around and flows back thru the full length of the module. To maximize the shielding function, the voidage permitted for these coolant passages was limited to 15%. Since the thermal capacity of the ceramic rod bundle is large relative to the thermal capacity of the helium coolant stream, it should be perfectly acceptable to maintain the same coolant flow thru both the plasma on and plasma off phase of the cycle and to withdraw the heat at the average rate based on 0.5 MW/m^2 .

Headers or manifolds are important inside each canister to insure uniform cooling of the canister wall and equally important external to the blanket proper to insure uniform flow to each of the blanket modules. A detailed analysis based on the methods of Acrivos [5] for the internal canister headers leads to the conclusion that the maximum deviation in flow is only 3% which should not present any problem. As might be anticipated for most of the flow path, the flow is turbulent then laminar as it approaches the end of the log. A summary of the aluminum blanket process conditions are shown in Table I.

TABLE I. TYPICAL THERMAL AND HYDRAULIC CHARACTERISTICS OF THE ALUMINUM BLANKET AT 0.5 MW(th)/m² (Avg) WALL LOADING FOR AN EPR

Nominal Reactor Power	300 MW	
Fraction of Power to Cold Circuit	0.45	
Fraction of Power to Hot Circuit	0.55	
Maximum First Wall Temperature, °C	400; Maximum Carbide Bed Temperature, °C 1450	
	<u>Cold Circuit Conditions</u>	<u>Hot Circuit Conditions</u>
Coolant	He	He
Inlet Temperature, °C	200	400
Outlet Temperature, °C	380	800
Operating Pressure, psia	600	300
Flow Rate, g/sec	2.87x10 ⁵	7.9x10 ⁴
Channel Velocity, m/sec	35	22
Heat Transfer Coefficient, w/cm ² -°C	0.35	0.08
Blanket Pressure Drop, psia	13.5	8
Pumping Power as Fraction of Total Power	0.022	0.01

4. GRAPHITE BLANKET-COOLING REQUIREMENTS

In this section we consider a significantly different blanket design. Of the low atomic number materials cited for blanket materials carbon or graphite is one such attractive material, and has been employed in a series of BNL designs [6,7].

The primary blanket is a thick screen of graphite blocks Fig. (4). Bremsstrahlung energy is deposited on the graphite surface and re-radiated away as thermal radiation so

that the first wall is radiatively cooled. All of neutron and gamma deposited energy is thermally radiated down cavities between the blocks or conducted through the blocks to the secondary blanket where it is absorbed by a row of SAP tubes cooled by high pressure helium. The graphite blocks are mounted on heavy Al backing plates, cooled by He, which are in turn supported from the fixed shield. The coolant tubes are protected by the primary blanket from radiation damage and should not require replacement during the life of an EPR. To reduce surface evaporation above 2000°C, the surface is radiatively cooled to a bank of coolant SAP tubes (the low temperature radiation sink) recessed from the graphite surface and protected by the graphite. Replacement of the sink may or may not be necessary during the life of an EPR. In the case that replacement is necessary it could be done much faster, the sink being located on the outer region of the torus, and cheaper than if the entire blanket were conventional.

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In order to evaluate the design potential of this new minimum activity blanket concept, 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 with the heat transfer computer code, CONRAD [8]. For the EPR case, $WL=1.0 \text{ MW(th)}/\text{m}^2$ with SAP coolant tubes at 400°C , we find that ~80% of the fusion energy is removed in the primary graphite-aluminum blanket while the remaining 20% is in the low-temperature sink. With a bulk graphite surface, 10% low temperature radiation sink the principal findings are: the graphite surface temperature, T_{max} , does not exceed $\sim 1800^\circ\text{C}$, the maximum surface temperature decreasing with an increase in the percentage of low temperature radiation sink area; the maximum heat pick up Q_{max} by the cooling tubes is $\sim 300\text{W}/\text{cm}$ during the plasma burn while Q_{min} is $\sim 285\text{W}/\text{cm}$ during the off-period of each pulse. These values are found to be essentially independent of cooling tube arrangement. The flow condition for the high pressure (50 atm) helium coolant is turbulent, with variable circumferential heat flux.

The most favorable conditions found for uniform heat pick up by the coolant tubes are: a) an L-shaped configuration of tubes; b) radiation gap between the SAP tubes and adjacent graphite; and c) by selectively surrounding the tubes with pyrographite, i.e., by surrounding only a few of the tubes with pyrographite and dependent on geometrical location in the tube matrix. The low conductivity direction is oriented perpendicular to the tube surface. The maximum to minimum heat pick up difference (with respect to uniformity of heat pick up by each tube per sec) is reduced to <2 to 1. Tube surface temperature excursions are negligible during the plasma on-off period. Of the thermal energy reaching the SAP tubes approximately 60% arrives via radiation down the cavity.

5. ACTIVATION LEVEL

For both blanket options the feasibility of hands-on maintenance is addressed. Dosage calculations for the blanket and shield are performed for a man standing outside the fixed shield (1 meter thick, with Al structure and B_4C and water coolant) 15 days after reactor shutdown, assuming a 1 year reactor operation. Results indicate that it should be possible to perform hands-on maintenance at selected areas on the outside surface of the shield. The dose to personnel would be less than 10^{-3} rem per day. All residual activations are allowed for in the blanket and shield including those of the bulk materials (Al, C, SiC, B_4C , H_2O , Al_2O_3) and whatever impurities can be expected. Nuclear calculations were made with 100 Group P_3S_8 ANISN runs for neutrons and 21 groups for gammas. All transmutations and decays are included to 2nd generation products.

6. CONCLUSIONS

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. Results indicate that it should be possible to perform hands-on maintenance at selected areas on the outside surface of the shield. Acceptable thermal power conversion efficiencies, i.e., 36.6% for the SAP module, can be achieved with low activity blankets.

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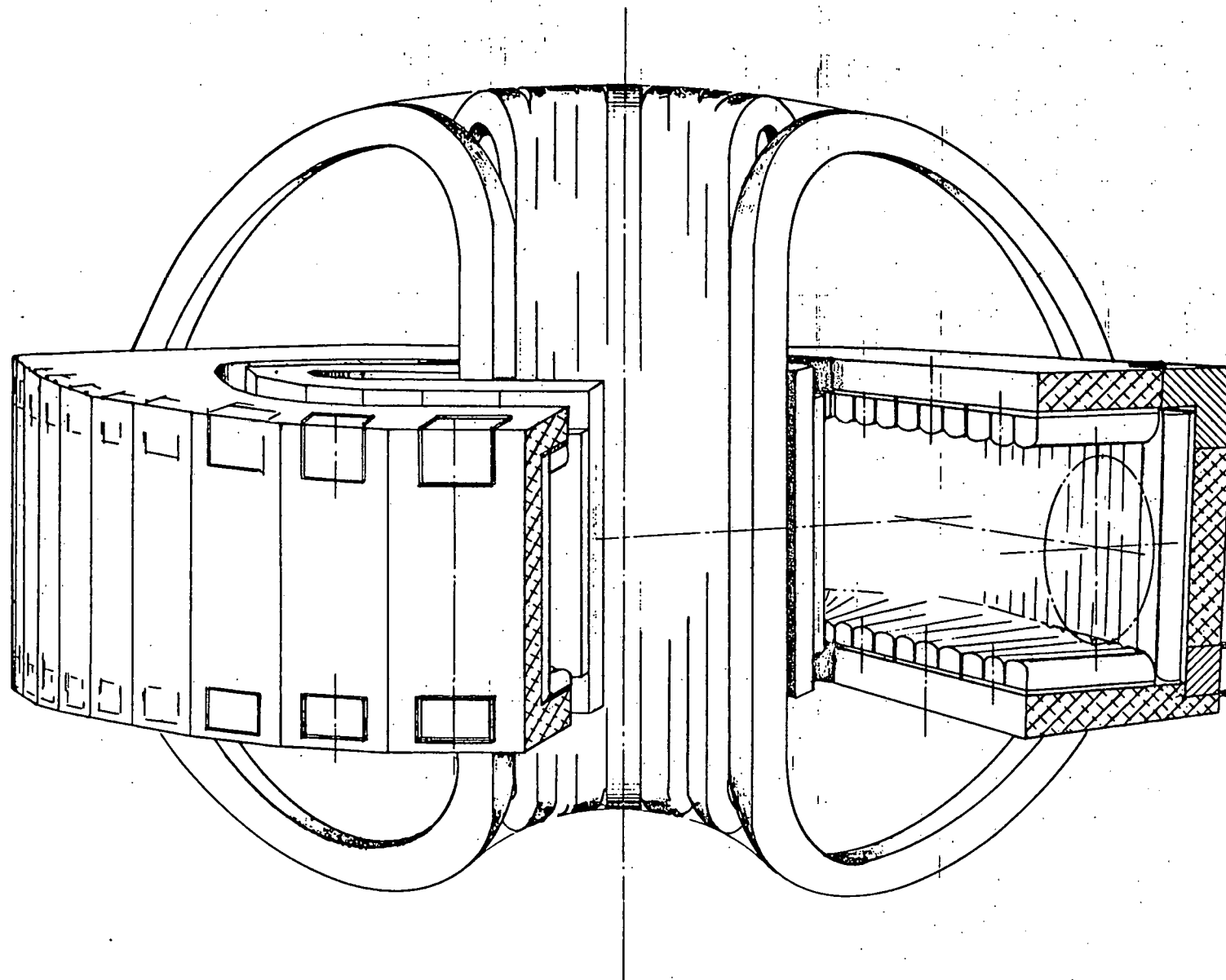
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Fig. 1 Schematic representation of tokamak reactor showing modular blanket concept

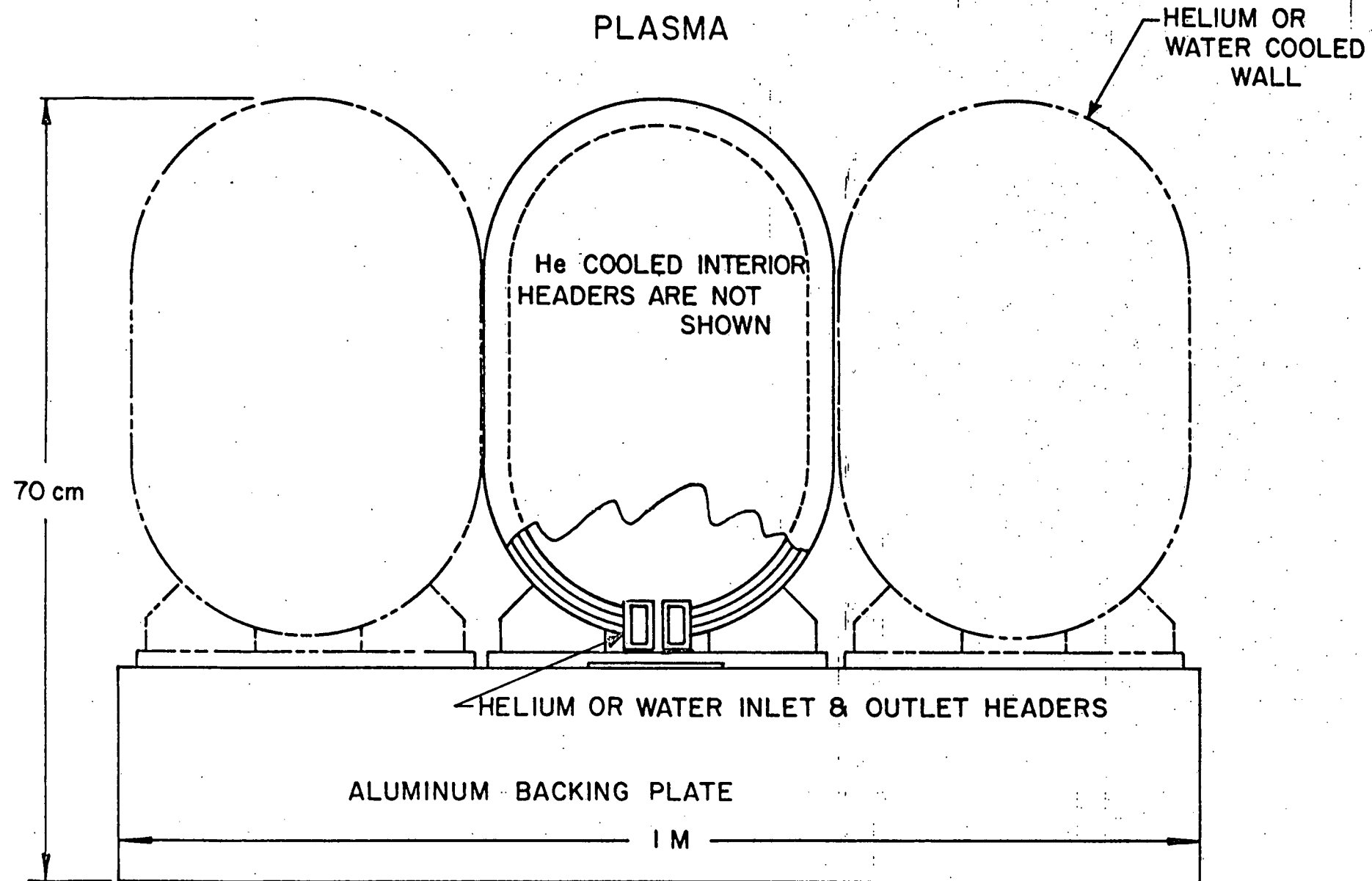
Fig. 2 EPR aluminum blanket module-triplet

Fig. 3 Typical shell cooling configuration

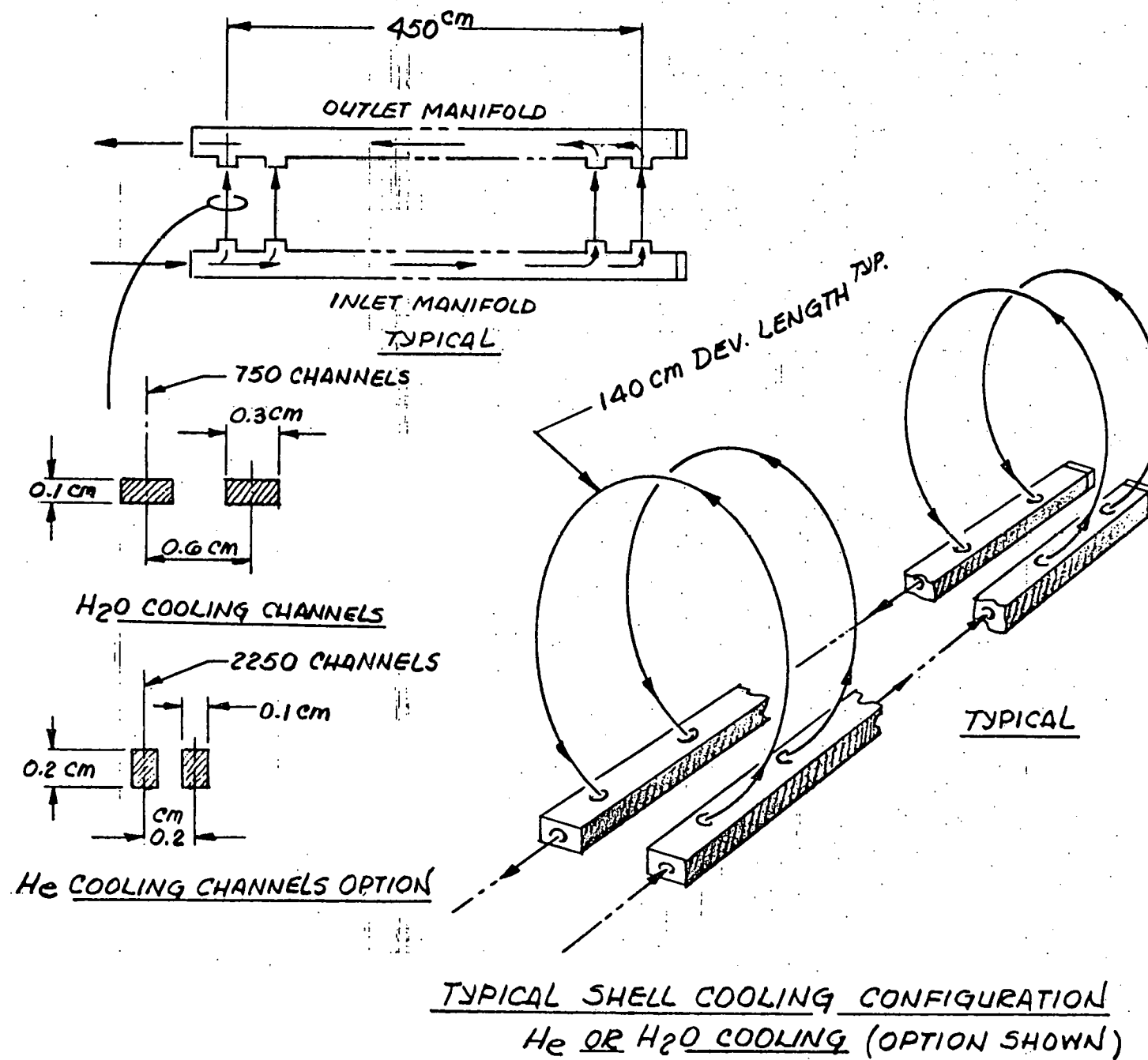
Fig. 4 EPR graphite blanket module

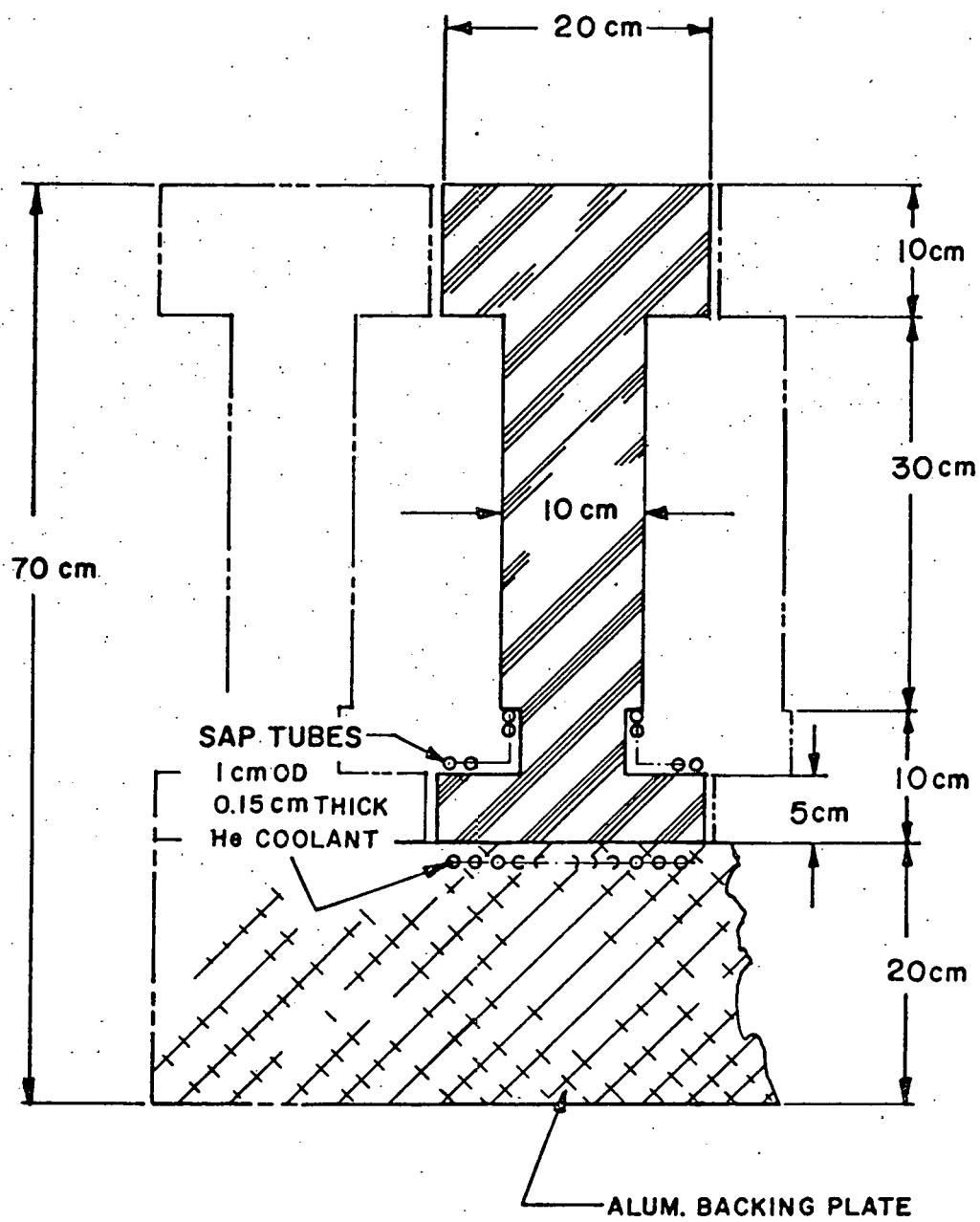


SCHEMATIC REPRESENTATION OF TOKAMAK REACTOR
SHOWING MODULAR BLANKET CONCEPT



MODULE SHOWING THREE INDIVIDUAL CANISTERS





EPR GRAPHITE BLANKET MODULE
CIRCULAR PLASMA