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## Abstract

A strategy is described for the design of lithium-cooled tokamak reactor blankets, and illustrated for a conceptual reactor system with 1167 MW thermal output. The calculated pressure drops, power consumption and heat transfer performance of the proposed blanket are very favorable. Considerable uncertainty exists, however, regarding operating life of structural materials under the unusual radiation conditions of such a reactor.

## Introduction

The Wisconsin fusion feasibility study group is currently working on D-T fueled toroidal reactors. A conceptual design is given in References 1-4 and is shown schematically in Figure 1; the system parameters are given in Table 1. The present paper gives an improved blanket design for this reactor, and indicates some important problems for further study.

The blanket of a D-T reactor has three main tasks: removing heat, breeding tritium, and moderating neutrons. These tasks have to be performed in the presence of intense radiation, high temperatures and strong magnetic fields. Magnetohydrodynamic effects are important, unless very low velocities are used for circulation of the breeding material (lithium or flibe)*. Thus, the design of a blanket is a complicated problem, requiring input from many disciplines. The design given here represents the latest iteration in a cooperative study of the whole reactor system[1], in which detailed consideration is being given to plasma physics, neutronics, magnets, divertors, materials, fueling, reactor safety, ecology and economics.

In this study, lithium is used both as the coolant and the breeding material; a graphite layer is used for neutron moderation. The use of lithium as a coolant requires careful attention to magnetohydrodynamic effects on the flow distribution, heat transfer and pressure drops. Early workers[5,6] reported unacceptably large

*$Li_2BeF_4$

pressure drops, but this difficulty has recently been reduced by more efficient coolant flow designs[4,7,8]. The present design represents a further improvement, such that lithium cooling appears very attractive for D-T reactor systems.

The combination of high magnetic field and electrically conducting coolant produces laminar flow throughout the blanket for all feasible coolant velocities. Thus the temperature profiles are predictable once the flow conditions are determined. The main problem in the blanket design is the selection of appropriate means to distribute the coolant flow, and to achieve good heat transfer effectiveness in a limited space without excessive power consumption or pressure drop.

## Design Strategy

The design given here is based on several simple rules obtained from Figure 1 and physical considerations:

1. Coolant must enter and leave the torus through the gaps between the curved portions of the D-shaped magnets.

2. The main headers inside the magnets should follow the torodial magnetic field lines to minimize pressure drops and utilize available space.

3. A large cross section should be provided for poloidal headers to minimize the pressure drops in these long flow paths perpendicular to the torodial field.

4. All the coolant should be routed to the first wall in well distributed radial ducts. The radial velocities should be small to minimize magnetohydrodynamic pressure drops, but large enough to avoid undesired heat exchange between adjacent radial streams.

## System Description

A design consistent with these ideas is shown in Figures 2 and 3. The reactor is a low-β Tokamak with four divertor slots; the main parameters are given in Table 1. The blanket structure is 316 stainless steel, and is designed with a maximum temperature of 500°C on the coolant walls to limit corrosion by the lithium. A corrosion loss of 2 mm and sputtering loss of 1 mm are included in the first wall thickness for a projected blanket life of 20 years.

The reactor has 12 independent modules, one for each magnet. Each module has four blanket units: one between the upper and lower divertors and three for the rest of the wall; see Figure 2. The coolant is supplied and removed through bundles of four pipes, rather than single large pipes, to reduce magnetohydrodynamic losses as discussed below. These bundles are connected to the torodial headers, which connect to poloidal headers that open into the radial flow cells as shown in Figure 3.

Each radial flow cell consists of four U-bends connected in series along the first wall. Series connection is used to decrease the residence time in each bend, and thus reduce undesired conduction of heat between adjacent radial streams[4]. To further reduce this exchange, the outlets of adjacent cells are juxtaposed; this requires provision of a different flow resistance in each cell to distribute the coolant properly. The U-bends are reinforced by poloidal tie-rods to maintain their alignment and contain the coolant pressure.

The alternating inward and outward radial flows in the U-bends produce corresponding alternations in the induced electric field [$\underline{v} \times \underline{B}$]. It is desirable to place the walls normal to this electric field to avoid short circuits between the adjoining radial streams. The arrangement in Figure 2 is consistent with this except for the small poloidal component of $\underline{B}$.

## Pressure Drops

The coolant pressure drop inside the reactor is almost entirely due to magnetohydrodynamic effects. It is calculated here by summing the following contributions as described by Hoffman and Carlson[9].

$$-\Delta p = K_{p1E}\, b\sigma \left|\Delta(vB_{\perp}^2)\right| \qquad \text{Entrance or Exit} \qquad (1)^*$$

$$-\frac{dp}{dx} = \frac{vB_{\perp}^2\, \sigma_w t_w}{a(1 + C)} \qquad \text{Steady flow in large uniform ducts} \qquad (2)$$

Equation 1 is applied here to changes in velocity, transverse magnetic field, or both. The coefficient $K_{p1E}$ is obtained from Figure 14 of Reference 9 by using $\Delta(vB_{\perp}^2)$ in place of $v\Delta(B_{\perp}^2)$. Equation 2 is an asymptotic result for $H_{\perp} \gg 1 + C^{-1}$, where $H_{\perp}$ is the transverse Hartmann number; this condition of validity is well satisfied here since $H_{\perp} \sim 10^5$ and $C \sim 0.1$.

The calculated pressure drops are summarized in Table 2 for each blanket unit. The calculations are based on local magnetic fluxes $\underline{B}$, including the poloidal and toroidal components. The resulting pressures are shown in Figure 4 for the unit between the divertors. The pressures are much lower than in the design of Reference 4; this is mainly due to changes in the feed and discharge tubes and in the structure of the poloidal headers. The maximum coolant pressure on the first wall is 175 psia. The pumping power required is 2.3 MW,

*Notation is at the end of the article.

which amounts to 0.2% of the reactor's thermal output.

Equation 1 indicates that a bundle of feed or discharge pipes gives less entrance pressure drop than a single pipe of the same total cross section, since both b and $K_{p1E}$ of Reference 9 increase with the pipe diameter. The pressure gradient of Equation 2, however, increases with decreasing pipe size when a corrosion allowance is included in $t_w$. The pressure gradient is reduced in this design by using laminated pipes with an electrical insulating layer protected by a thin inner wall of stainless steel. An inner wall thickness $t_w$ of 2 mm is used to withstand corrosion by the lithium; a heavier outer wall carries the hoop stress.

The poloidal headers are designed with similarly laminated walls to reduce pressure drop, and also to reduce heat exchange between the adjoining streams. An alternative to electrical insulation is to use tapered headers[4] to equalize the induced voltages in adjacent headers.

Rectangular orifices are used to connect the poloidal headers to the radial flow cells. The pressure drop, according to Equation 1, is nearly proportional to vb = V/a, where V is the volumetric flow and a is the orifice width in the polodial direction. This gives the surprising result that the pressure drop is independent of the orifice length b in the the toroidal direction. For purposes of flow distribution, b is taken here as the full poloidal header width.

The pressure gradient in the radial flow cell is due mainly to eddy currents, which flow through the fluid in the direction of $[\underline{v} \times \underline{B}]$ and return through the poloidal tie-rods. Radial flow is thus resisted by the toroidal magnetic field, but toroidal flow is not; this causes the flow to distribute readily over the toroidal length of each heat removal cell. For these cells, $t_w/a$ of Equation 2 is taken as the ratio of the conducting cross sections of the tie-rods and fluid.

## Wall Stresses

The maximum pressure at the first wall of the blanket is 175 psia. To contain this pressure and impart rigidity to the blanket, we use a wall of toroidal half-tubes as shown in Figure 2. A tube size of 7.5 cm is used; larger sizes give larger total stresses in the first wall.

The local stress in the wall is the resultant of the thermal and hoop stresses. The maximum stress occurs on the coolant side of the wall where both stresses are tensile. Figure 5 shows these stresses and their sum as functions of the wall thickness. The combined stress goes through a minimum at a wall thickness of 2.5 mm. With allowance for a 3 mm loss by corrosion and sputtering, 4.5 mm is a reasonable initial thickness.

## Temperature Distribution

Steady state temperature profiles have been calculated for a radial flow cell on the assumptions of negligible temperature changes in the headers and uniform fluid speed throughout the cell. The uniform speed assumption is adequate in view of the high transverse Hartmann numbers and small Peclet numbers encountered in this design. The calculation was done as in Reference 4, by an implicit finite-difference method with a two-dimensional point mesh conforming to the streamlines. The surface and volumetric heat input rates were taken from neutronics calculations reported for a similar blanket in Figure 6 of Reference 1. The inputs were normalized upward to compensate for the neglect of heat generation in the headers; thus the calculated temperature gradients are conservative (larger than actual) by about 20%.

The calculated coolant temperatures in a radial-flow cell are summarized in Figure 6. The main conclusion to be drawn is that the coolant can be discharged at a temperature quite close to the structural material corrosion limit of 500°C. The temperature approach is closer than in Reference 4 because the coolant residence time is more nearly optimal.

## Discussion

An efficient design has been proposed for a lithium-cooled reactor blanket. The same type of design is adaptable to other wall loadings and magnetic fields over the expected range for toroidal fusion reactors.

Present knowledge appears to be adequate for detailed calculation of the fluid velocity, pressure, and temperature profiles throughout the blanket. The calculations made here are approximate, but sufficient to establish the feasibility of the design.

The main uncertainty in blanket design lies in the lack of information on degradation of the structural materials in the reactor. Swelling and embrittlement will occur, especially in the first wall, under the intense high-energy neutron radiation.[10] Research is urgently needed on these effects and on radiation-resistant materials. Work is also needed on alternate blanket designs to facilitate replacement of the first wall, or to eliminate the need for a solid wall as in the Blascon reactor concept.[11]

## Acknowledgement

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## Notation

$a$ effective half-width of the flow cross-section in the direction of $B_\perp$

$B_\perp$ transverse component of the magnetic field

$b$ effective half-width of the cross-section in the direction of the magnetic field ( $a = b = \pi D/8$ for a pipe of diameter D)

$C$ $= \sigma_w t_w / \sigma a$, ratio of wall and fluid conductances

$K_{p1E}$ dimensionless function of geometry and wall conductance ratio C, given in Figure 14 of Reference 9

$p$ coolant pressure

$t_w$ wall thickness

$V$ Volumetric flow rate

$v$ coolant velocity

$\sigma$ electrical conductivity of the coolant

$\sigma_w$ electrical conductivity of the wall material

## Table I

Design Specifications for Fusion Reactor, Ref. (1)

| | |
|---|---|
| Major radius | 12.5m |
| Minor radius | 2.8m |
| Maximum magnetic field | 8.6 Tesla |
| Thermal output | 1167 MW |
| Nominal wall loading | 0.85 $MW/m^2$ |
| Structural material | 316SS |
| Coolant | Lithium |
| Maximum coolant temperature | 500°C |
| Coolant temperature rise | 200°C |
| Blanket materials | |
| Lithium | 0.50m |
| Graphite | 0.25m |
| 316SS | 0.03m |

## REFERENCES


1. Abdou, M. A., et. al. "Preliminary Conceptual Design of a Tokomak Reactor," Texas Symposium on the Technology of Controlled Thermonuclear Fusion Experiments and the Engineering Aspects of Fusion Reactors, 1972.

2. Conn, R. W. , McAlees, D. G. , Emmert, G. A., "Self-Consistant Energy Balance Studies for CTR Tokamak Plasmas," Texas Symposium, 1972.

3. Young, W. C., and Boom, R. W., "Materials and Cost Analysis of Constant-Tension Magnet Windings for Tokamak Reactors," Fourth International Magnet Conference, Brookhaven, 1972.

4. Sze, D. K. , and Stewart, W. E., "Lithium Cooling for a Low-β Tokamak Reactor," Texas Symposium, 1972.

5. Homeyer, W. G., "Thermal and Chemical Aspects of the Thermonuclear Blanket Problem," Research Laboratory of Electronics, M. I. T., TR435, 1965.

6. Hancox, R., and Booth, J. A., "The Use of Liquid Lithium as a Coolant in a Toroidal Fusion Reactor," UKAEA Culham Laboratory Report CLM-R 115 and 116, 1971.

7. Mitchell, J. T. D., and Hancox, R., "A Lithium Cooled Toroidal Fusion Reactor," Energy '72, San Diego.

8. Fraas, A. P., "Conceptual Design of the Blanket and Shield Region of a Full Scale Toroidal Fusion Reactor," USAEC Report ORNL-TM-3096, 1972.

9. Hoffman, M. A., and Carlson, G. A., "Calculation Techniques for Estimating the Pressure Losses for Conducting Fluid Flows in Magnetic Fields," USAEC Report UCRL-51010, 1971.

10. Kulcinski, G. L., "Major Technological Problems for Fusion Reactor Power Stations," International Conference on Nuclear Solutions to World Energy Problems, Washington, D. C., 1972.

11. Steiner, D., "Review of ORNL Fusion Reactor Technology Studies," Texas Symposium, 1972.

Table II

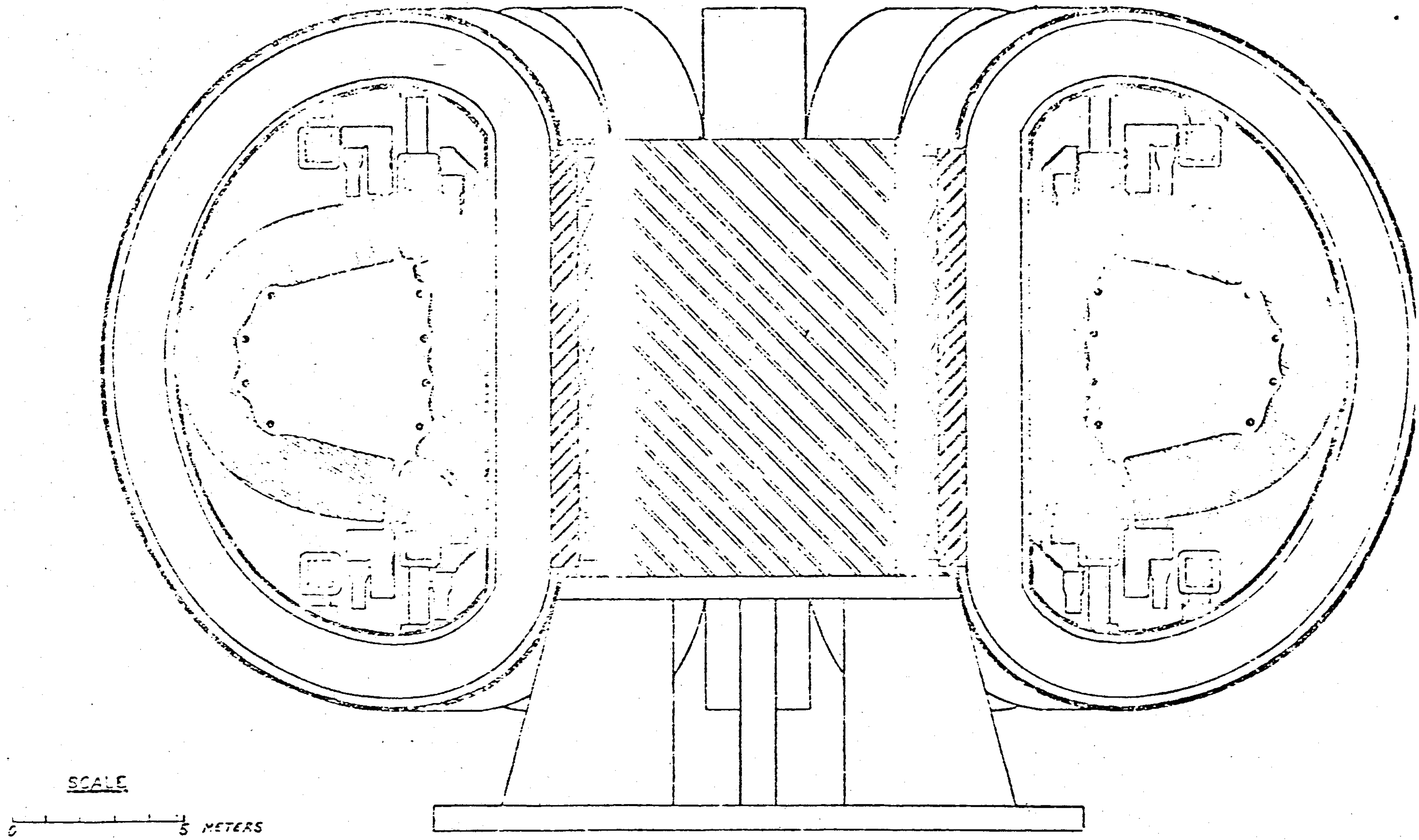
Summary of Pressure Drop Calculations

| | v, m/s | b, m | $L_F/b$ | $K_{plE}$ | $t_w$, mm[b] | L, m | $B_\perp$, tesla | Pressure Drops, psi: Entrance, Exit | Pressure Drops, psi: Duct Flow | Pressure Drops, psi: Total |
|---|---|---|---|---|---|---|---|---|---|---|
| **2a. Unit between the divertors (see Figure 2)** | | | | | | | | | | |
| Feed pipe; discharge pipes | .112 | .196 | 5.1 | .05 | 2.0[c] | 1.0 | 8.6 | 58 | 5 | 63 (x2) |
| Toroidal headers | .448 | .196 | - | - | 4.0 | 6.0 | .8 | - | 6 | 6 |
| Connecting channels | .055 | .1 | 1.0 | .16 | 2.0[c] | 4.0 | 8.6 | 17 | 21 | 38 (x2) |
| Poloidal headers | .073 | .1 | - | - | 2.0[c] | 6.0 | 8.6 | - | 42 | 42 |
| Radial cells | .024 | .5[a] | 1.0 | .16 | 3.0 | 1.6 | 8.6 | 7 | 7 | 14 |
| | | | | | | | | | | 264 |
| **2b. Unit on top and bottom of the torus** | | | | | | | | | | |
| Feed pipes | .075 | .196 | 5.1 | .05 | 2.0[c] | 6.0 | 5.2 | 14 | 7 | 21 |
| Toroidal headers | .295 | .196 | - | - | 4.0 | 6.0 | .5 | - | 4 | 4 |
| Poloidal headers | .049 | .1 | 1.0 | .16 | 2.0[c] | 4.0 | 5.2 | 3 | 4 | 7 |
| Radial cells | .24 | .5[a] | 1.0 | .16 | 3.0 | 1.6 | 5.9 | 7 | 4 | 11 |
| Discharge pipes | .075 | .196 | 5.1 | .05 | 2.0[c] | 3.0 | 4.5 | 11 | 3 | 14 |
| | | | | | | | | | | 57 |

Table II cont.

| | $v$, m/s | $b$, m | $L_F/b$ | $K_{p1E}$ | $t_w$, mm[b] | $L$, m | $B_\perp$, tesla | Pressure Drop, psi: Entrance, Exit | Pressure Drop, psi: Duct Flow | Pressure Drop, psi: Total |
|---|---|---|---|---|---|---|---|---|---|---|
| **2c. Unit farthest from magnet axis (see Figure 2)** | | | | | | | | | | |
| Feed pipe (discharge) | .075 | .196 | 5.1 | .05 | 2.0[c] | 3.0 | 3.7 | 7 | 2 | 9 (x2) |
| Toroidal headers | .295 | .196 | - | - | 4.0 | 6.0 | .4 | - | 2 | 2 |
| Poloidal Headers | .049 | .1 | 1.0 | .16 | 2.0[c] | 4.0 | 3.7 | 2 | 2 | 4 |
| Radial cells | .024 | .5[a] | 1.0 | .16 | 3.0 | 1.6 | 3.7 | 7 | 3 | 10 |
| | | | | | | | | | | 34 |

[a] Effective value based on $C = \pi R^2 N\sigma_w/\sigma$ with $N = 100$ tie-rods/m$^2$ of baffle, and tie-rod radius $R = 0.006$ m.
[b] Values based on initial wall thickness, with corrosion allowances of 1 mm or 2 mm according to flow velocity.
[c] Pipe designed with laminated wall; inner layer of SS 316, 2 mm thick, shields electrical insulating layer from lithium.

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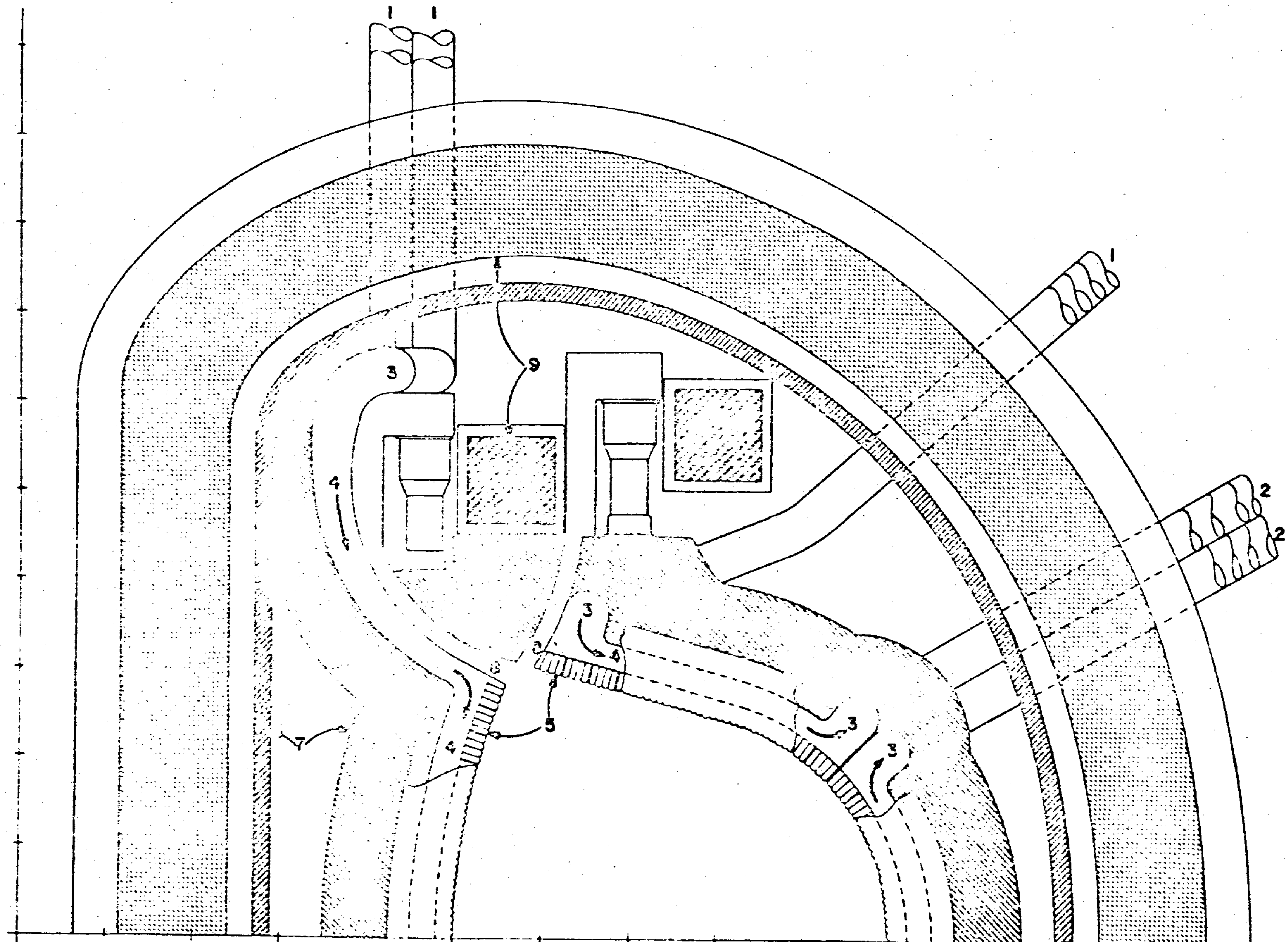



FIG. 2. SECTION VIEW OF A TOROIDAL MODULE

1. FEED PIPES
2. DISCHARGE PIPES
3. TOROIDAL HEADERS
4. POLOIDAL HEADERS AND CONNECTORS
5. RADIAL FLOW CELLS
6. GRAPHITE
7. SHIELD
8. DIVERTOR SLOTS
9. SUPERCONDUCTING MAGNETS

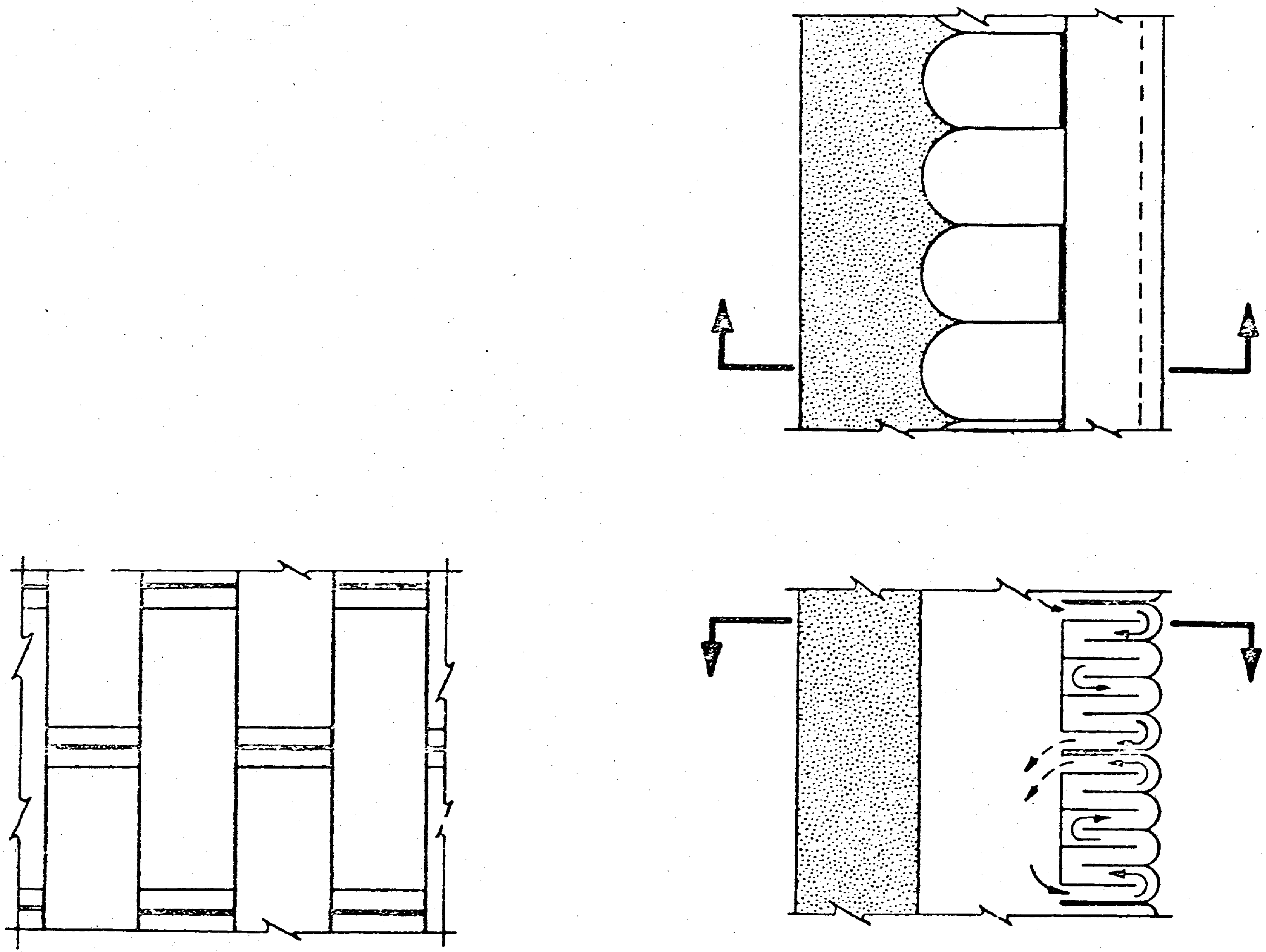


FIG. 3 Section Views of Blanket

FIG. 4. COOLANT PRESSURE DISTRIBUTION

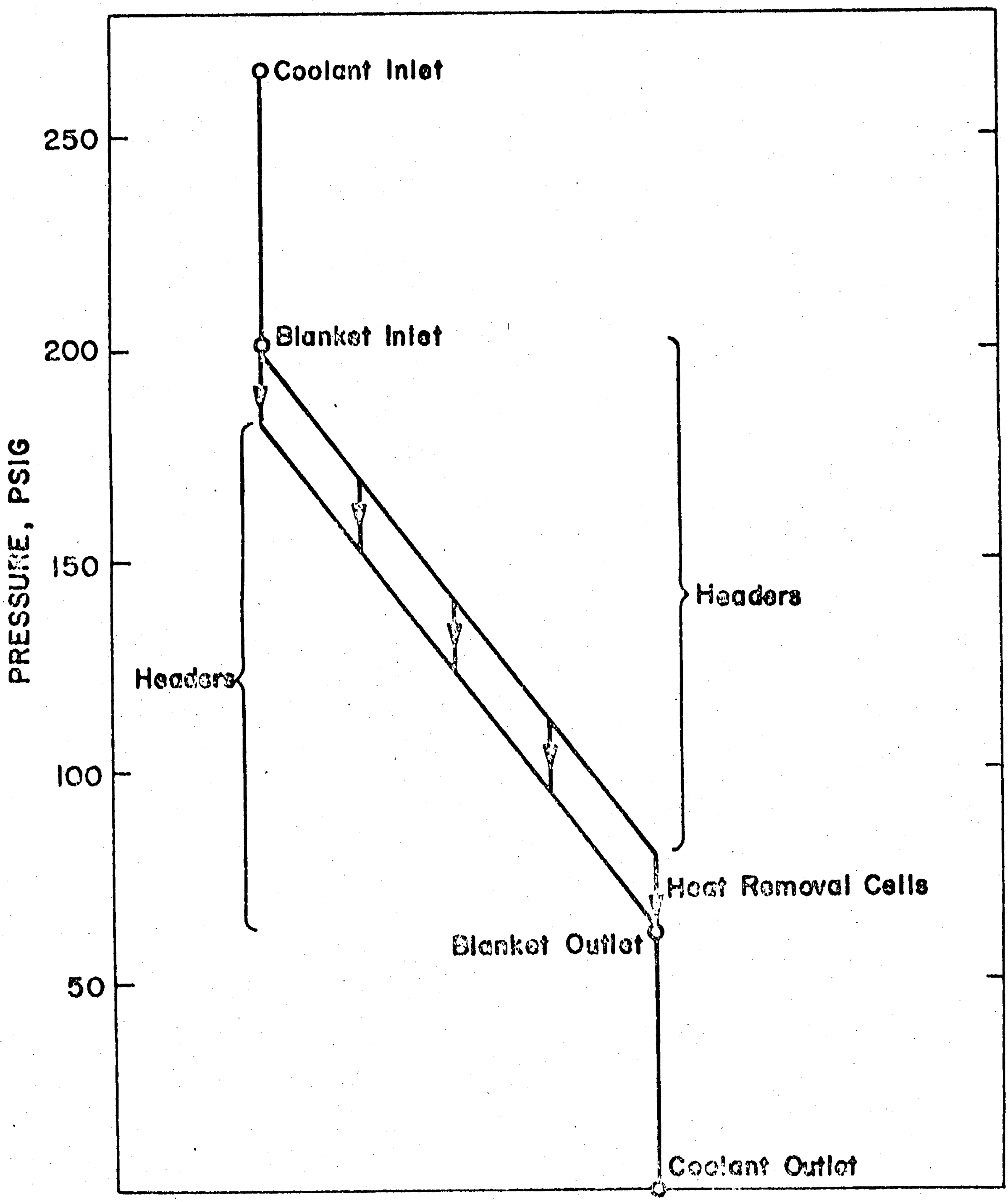
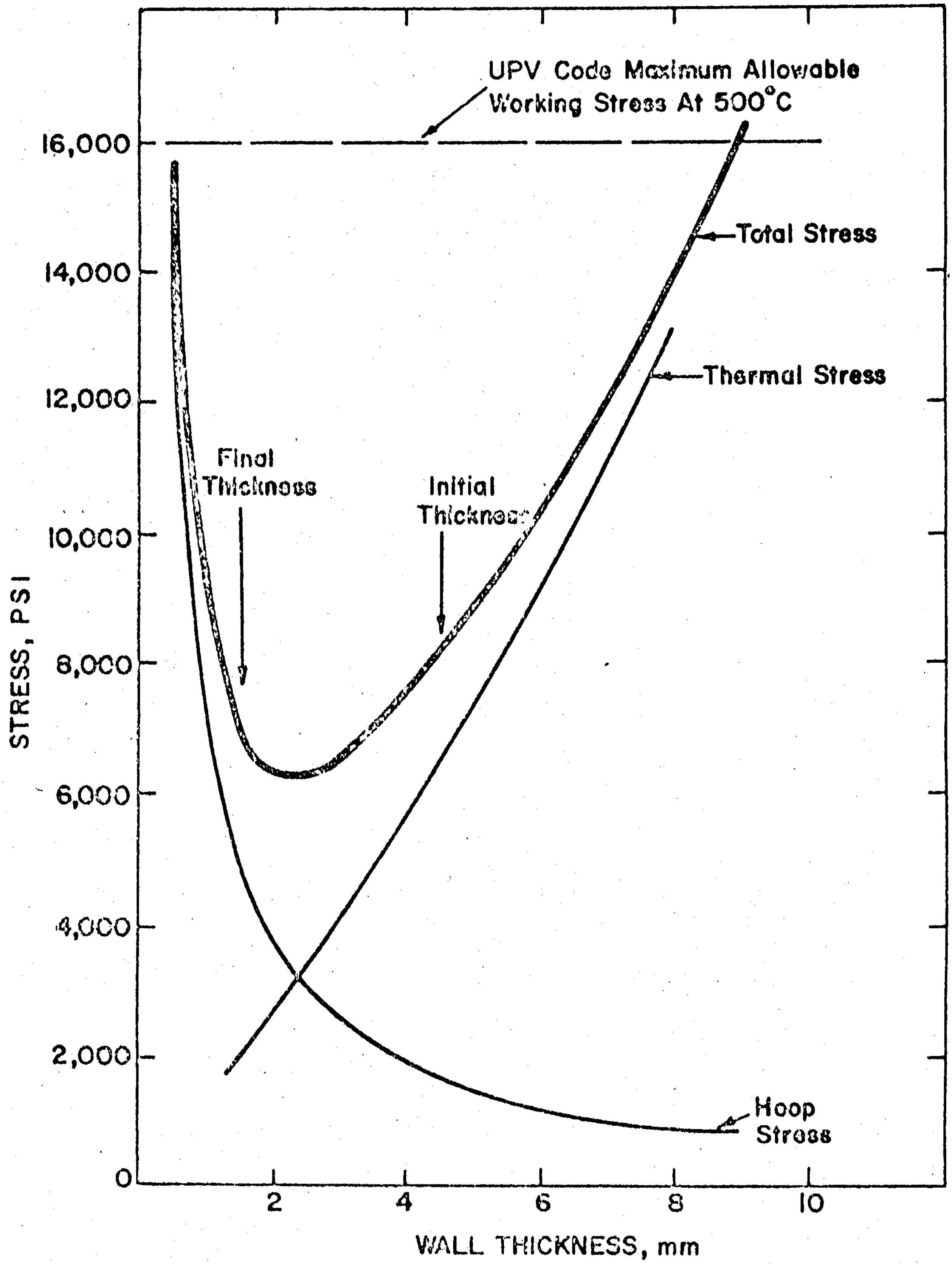


FIG. 5. STRESSES IN THE FIRST WALL AS FUNCTIONS OF WALL THICKNESS



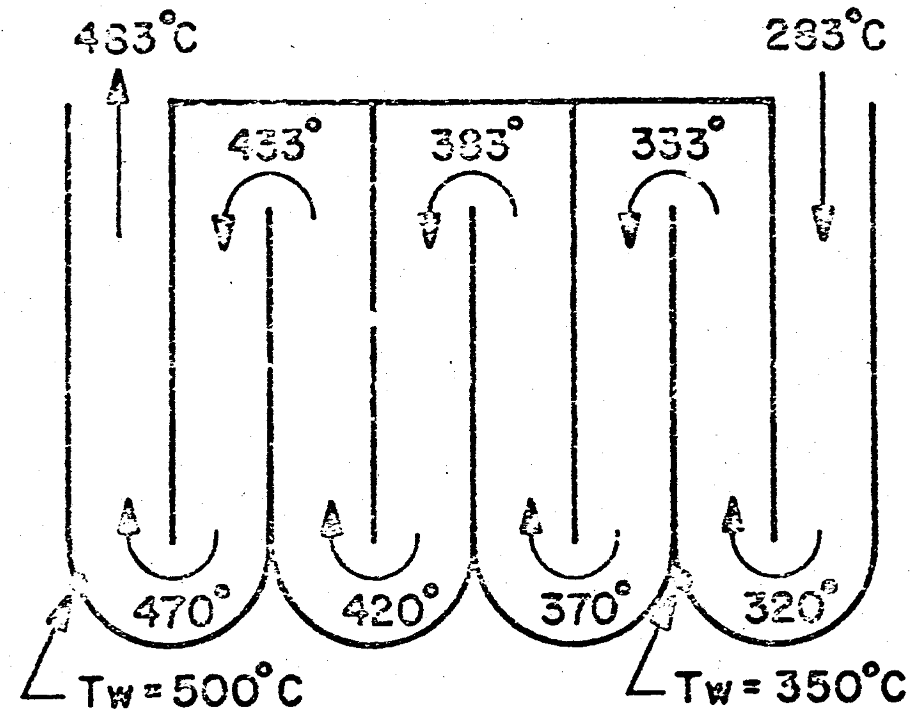



FIG. 6. BULK AND MAXIMUM COOLANT TEMPERATURES IN A RADIAL FLOW CELL