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ABSTRACT

A conceptual blanket design, based on lithium coolant, is proposed for a D-T fusion reactor. The reactor is a Tokamak made of 316 stainless steel with major and minor diameters of 12.5 and 2.8 meters. The maximum magnetic field is 86 kilogauss. The nominal wall loading is 0.85 mw/m^2, and the maximum temperature on the first wall is 500 C.

The flow configuration is a compromise between power consumption and thermal efficiency. The power required for pumping is moderate, and some power is sacrificed to reduce thermal feedback problems. The magnetic field is utilized to control the flow distribution within the blanket. The effects of thermal stress and hoop stress in the first wall are considered.

INTRODUCTION

The blanket of a D-T fusion reactor has to perform the following tasks:

1. Heat removal.
2. Tritium breeding.
3. Neutron moderation.

For heat removal, various coolants have been proposed; the usual ones are lithium, flibe and helium. For tritium breeding, the blanket must contain either pure lithium or a lithium salt, such as flibe (F_4Li_2Be). For neutron moderation, a graphite layer is commonly included.

For the present study, we have chosen lithium as the coolant and the breeding material, for the following reasons:

1. The low wall loading (dictated by radiation damage considerations[1]) permits use of lithium without excessive pressures or pumping costs.
2. Lithium-cooled systems tend to be simpler than flibe or helium systems.
3. The heat generation in the first wall would be significantly increased by γ-radiation (backshine) if flibe were used.
4. The availability of beryllium, a component of flibe, is in doubt.[2]

The main problem with lithium is the difficulty of transporting it across magnetic fields. Early work on lithium cooling[3] gave very high pressure drops for the high wall loadings considered there. However, with the recent trend to lower wall loadings, interest in lithium as a coolant has increased.[1,4]

REACTOR SYSTEM

The reactor considered here is a low-β Tokamak made of 316 stainless steel. The major and minor diameters are 12.5 and 2.8 meters. The power output of the reactor is 1167 mw(t), which corresponds to a wall loading of 0.85 mw/m^2. The thickness of the blanket is 1.0 m. The heat generation rates for a stainless steel structure are not yet available; hence, the results for a niobium structure are used. The resulting differences in heat generation rates are estimated to be small within the blanket, but may be significant in the first wall. The maximum temperature in the first wall is taken as 500 C to limit the rate of corrosion of the stainless steel by the lithium. Our calculations are based on a combined corrosion and sputtering loss of 0.1 mm/yr for the first wall, and an operating cycle of 20 years.

The reactor is made up of 12 independent modules, one for each magnet. A schematic view of one module (30° of torus) is shown in Figure 1. Within each module there are three cooling units: one in the inner space between the divertors and two on the outer side. The unit between the divertors is the most critical, because the magnets are closer together there, and the magnetic field strength is near its maximum.

The calculations given below are for this region.

Figures 1, 2, and 3 show the coolant flow scheme. Each cooling unit is connected to the outside by a feed pipe and a discharge pipe. These pipes connect with toroidal headers inside the blanket, running parallel to the main magnetic field. The toroidal headers open into poloidal headers, running perpendicular to the main magnetic field. The two sets of headers occupy the outer 0.3 m of the blanket, thus providing large flow cross sections to avoid excessive pressure drops. The poloidal headers are connected to heat removal cells which cover the first wall as shown in Figure 3. A graphite moderator-reflector, 0.2 m thick, is provided between the headers and the heat removal cells. The radial baffles of the heat removal cells are braced by poloidal tie rods to maintain their alignment.

DESIGN GUIDELINES

Two main considerations have been used in designing the coolant channels:

1. To avoid large pressure drops, low velocities have been used, especially in crossing magnetic field lines. Thus, the poloidal headers and radial flow passages, as well as the feed and discharge pipes, have been designed with large total cross sections.
2. To achieve a high heat transfer effectiveness,

$$\eta = \frac{T_{coolant\ out} - T_{coolant\ in}}{T_{first\ wall,\ max.} - T_{coolant\ in}} , \quad (1)$$

all the coolant is made to flow close to the first wall, and the hot and cold streams are segregated.

PRESSURE DROPS

The coolant pressure drop across the reactor is dominated by magnetohydrodynamic effects. We have estimated these from the following equations, recommended by Hoffman and Carlson:[5]

1. Entrance or exit from magnetic field:

$$-\Delta p = K_{p1E}\, \sigma\, b \left| \Delta (v B_{\perp}^2) \right| \tag{2}$$

Here σ is the electrical conductivity of the fluid;

v is the mean velocity;

b is the channel half-width in the direction of the field (here taken as $\pi D/8$ for a pipe of diameter D);

$B_{\perp}$ is the magnetic field component normal to the mean velocity in the given cross section;

K_{p1E} is a dimensionless function of geometry and wall conductance ratio, given in Figure 14 of Reference 5.

Notational changes have been made here to allow estimation of Δp for gradients in the velocity vector $\underline{v}$, as well as gradients in the magnetic field $\underline{B}$.

2. Developed flow in straight channels (limit for high transverse Hartmann number, $H \equiv a B_{\perp} \sqrt{\sigma/\mu}$):

$$-\frac{dp}{dx} = \frac{\mu v}{a^2} \frac{H^2 C}{1+C} = \frac{v B_{\perp}^2 \sigma_w t_w}{a(1+C)} \tag{3}$$

Here μ is the fluid viscosity;

a is the effective half-width of the flow cross-section, in the direction of $B_\perp$. For a circular cross section $a = R/1.3$;

σ_w is the electrical conductivity of the wall;

t_w is the wall thickness;

C is the wall conductance ratio, $\sigma_w t_w/\sigma a$.

Upper bounds on the pressure drops have been estimated by adding the predictions of Eqs. (2) and (3) for each region. The calculations are summarized in Table 1 and Figure 4. The overall pressure drop is about 380 psi for the blanket, and 290 psi for each of the feed and discharge pipes. The required power input to the fluid is 20.8 mw, or 1.8% of the reactor's thermal output.

HEAT TRANSFER

Finite-difference calculations have been made for the temperature profiles in a representative portion of a heat removal cell (Figure 5). By treating the temperature changes for successive U-bends as additive, we get the following results for one heat removal cell containing four U-bends:

	First U-Bend	Second U-Bend	Third U-Bend	Fourth U-Bend
T_{in}	275	325	375	425 C
T_{out}	325	375	425	475 C
T max, first wall	350	400	450	500 C

If only one U-bend is used in each cell, with the same total coolant temperature rise, the calculated values are:

T_{in}	78 C
T_{out}	278 C
T max, first wall	500 C

This is clearly unacceptable, since lithium solidifies at 186 C. The poor performance of such a unit is due to the thermal feedback caused by the lower coolant velocity and the shorter heat flow path between the hot and cold streams.

DESIGN CONSIDERATIONS FOR THE FIRST WALL

Stainless steel is generally discounted as a first wall material because of thermal stress considerations. However, with the small wall loadings now contemplated, and with the added considerations of availability, cost and ease of fabrication, stainless steel is a reasonable choice.

The first wall faces the vacuum, and thus must bear a maximum pressure difference of 622 + 15 = 637 psi. To contain this pressure and impart rigidity, we use a wall of toroidal half-tubes as shown in Figure 1. A tube size of 7.5 cm is chosen; larger sizes give larger stresses in the wall.

The first wall is subjected to thermal stress and hoop stress. The sum of these two is the total stress in the wall material facing the plasma. Figure 6 shows these stresses as functions of the wall thickness.[6] The minimum stress occurs in a wall approximately 4 mm thick. The initial wall thickness is chosen as 5 mm, to allow for corrosion and sputtering over a 20 year period.

For cyclic reactor operation, the stresses will vary with time, and the fatigue limits of the wall material will need to be considered.

CONCLUSIONS

This study indicates that lithium cooling is feasible for D-T fusion reactors in the range of wall loadings and magnetic field strengths considered here. The power consumption is moderate and the pressures are acceptable.

The results obtained here suggest some important areas for future work. The pressure drops and power consumption are tolerable for this design, but it would be desirable to alleviate them so as to handle higher mass flows and higher magnetic fields. The thermal performance can also be improved, by varying the connections of the heat removal cells.

ACKNOWLEDGMENT

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Table 1

SUMMARY OF PRESSURE DROP CALCULATIONS

	v, m/s	b, m	L_F/b	K_{p1E}	t_w, mm	L, m	Pressure Drop, psi: Entrance	Hartmann	Total[g]
ipe; rge Pipe	0.448	0.196	5.1	0.05	2.0[e]	2.5	235	55	290
al s	0.59	0.14	–	–	4.0	6.0	–	8	8
al s	0.073[a]	0.035[a]	1.	0.16	3.0[f]	6.0	10	260	270
te	0.023[b]	0.15	1.	0.16[d]	2.0	0.3	30	3	33
Removal	0.024	0.5[c]	–	–	5.0	4.0	–	35	35

rs tapered to maintain constant v along their length; average width = 0.069 m.

on slotted passages 0.038 m x 0.3 m, with openings 0.038 m x 0.069 m into header.

tive value based on $C = \pi R^2 N \sigma_w / \sigma$, with N = 160 tie-rods/$m^2$ of baffle, and tie-rod radius R = 0.006 m.

bound, estimated by use of maximum velocity and maximum channel width.

designed with laminated wall; inner layer of SS 316, 2 mm thick, shields electrical insulating er from lithium.

l wall thickness is 6.0 mm; half of this is associated with each adjoining stream, since the ocities are equalized by tapering these headers.

s based on initial wall thicknesses, with corrosion allowances of 1 mm or 2 mm according to v velocity.

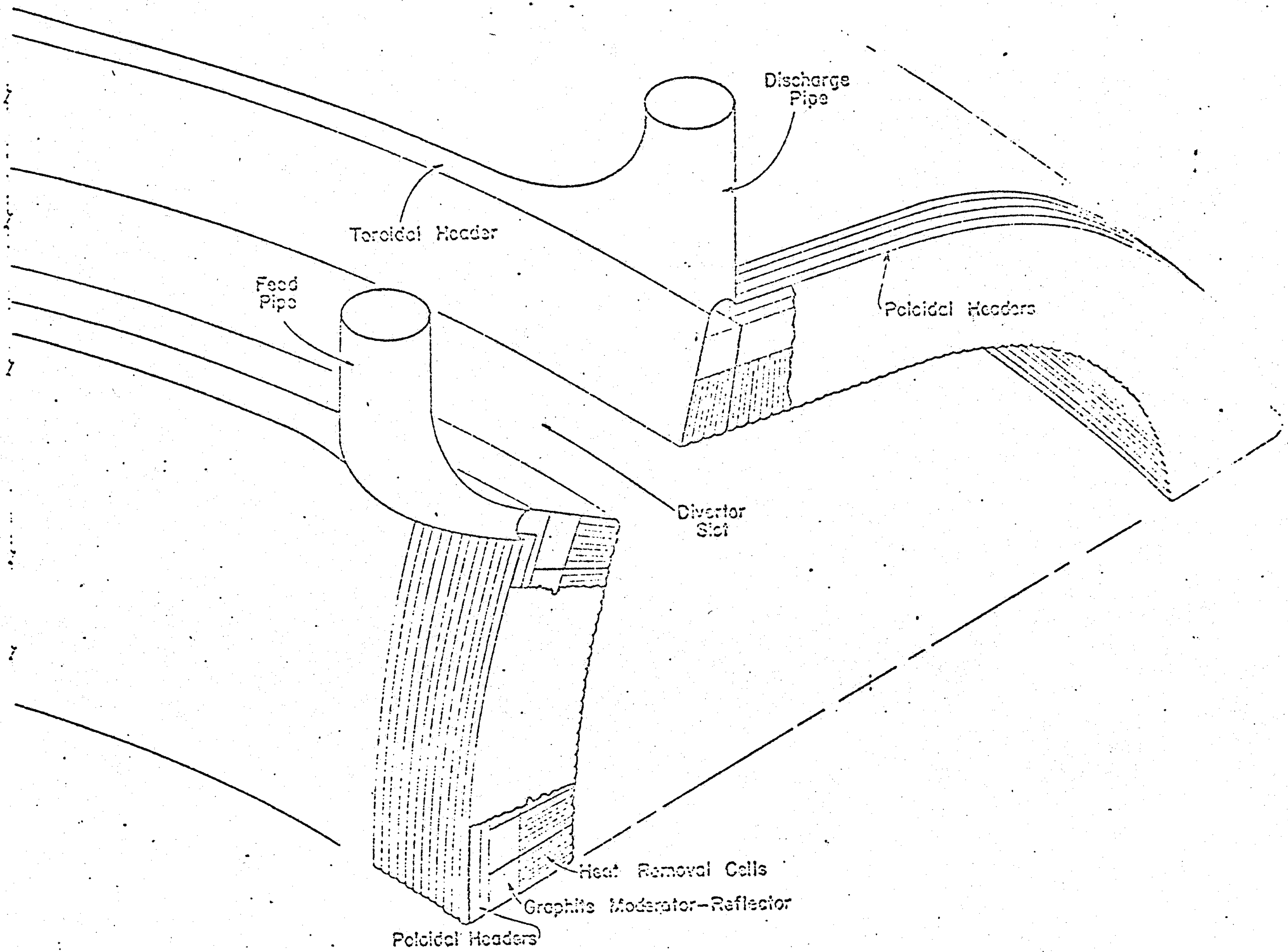


FIG.1 Schematic View of a Blanket Module

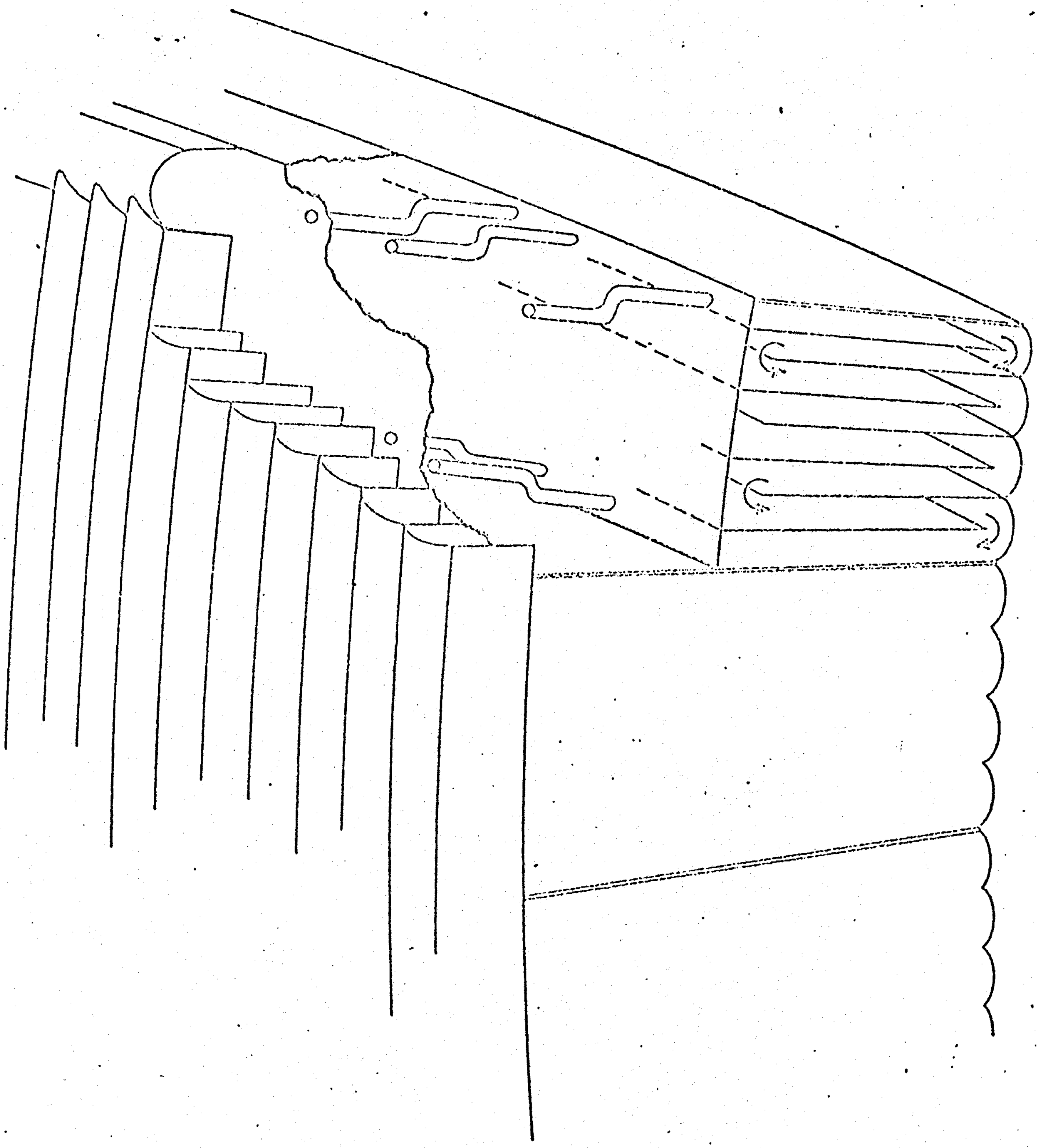


Fig. 2 Cutaway View of Blanke

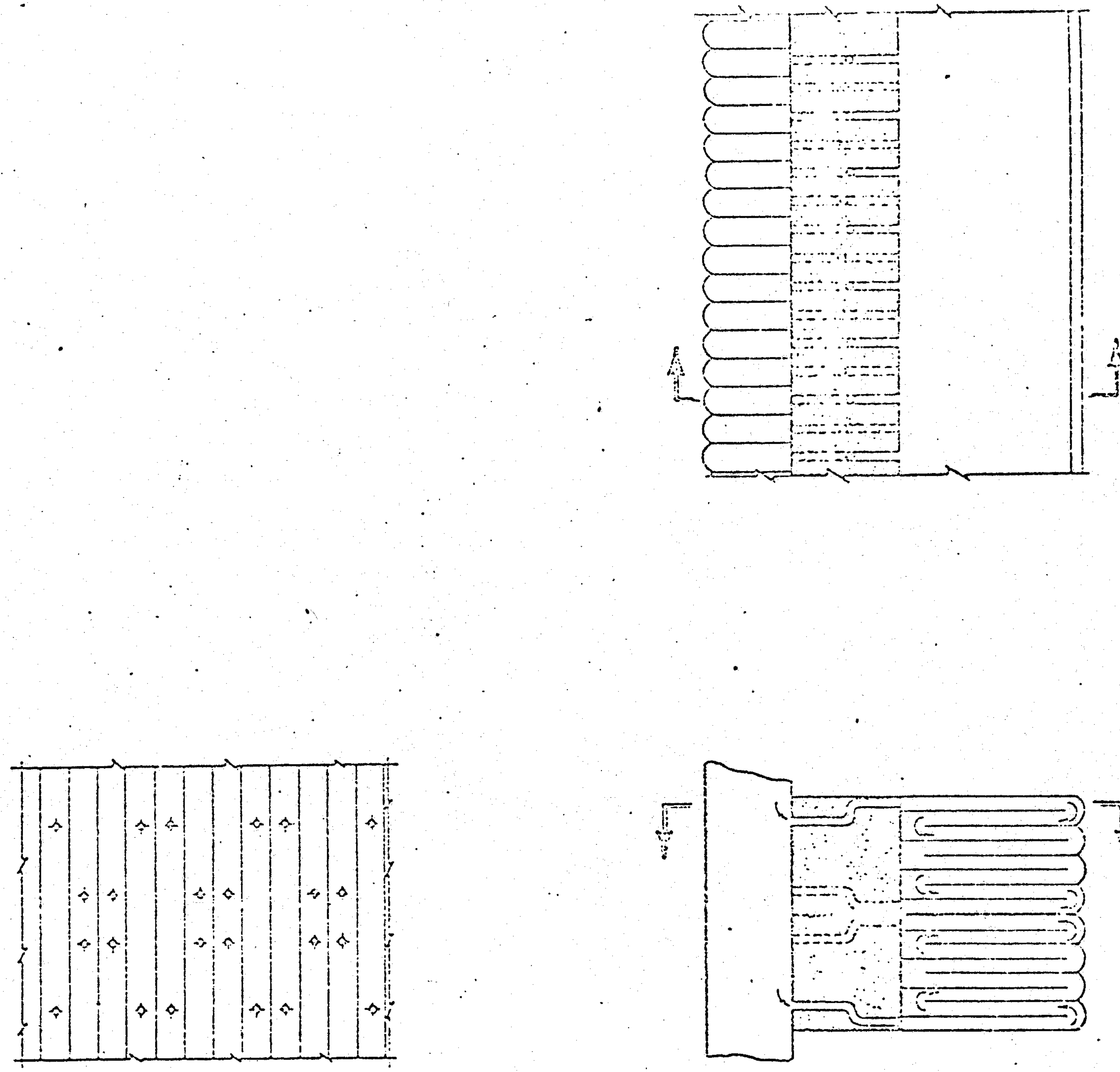
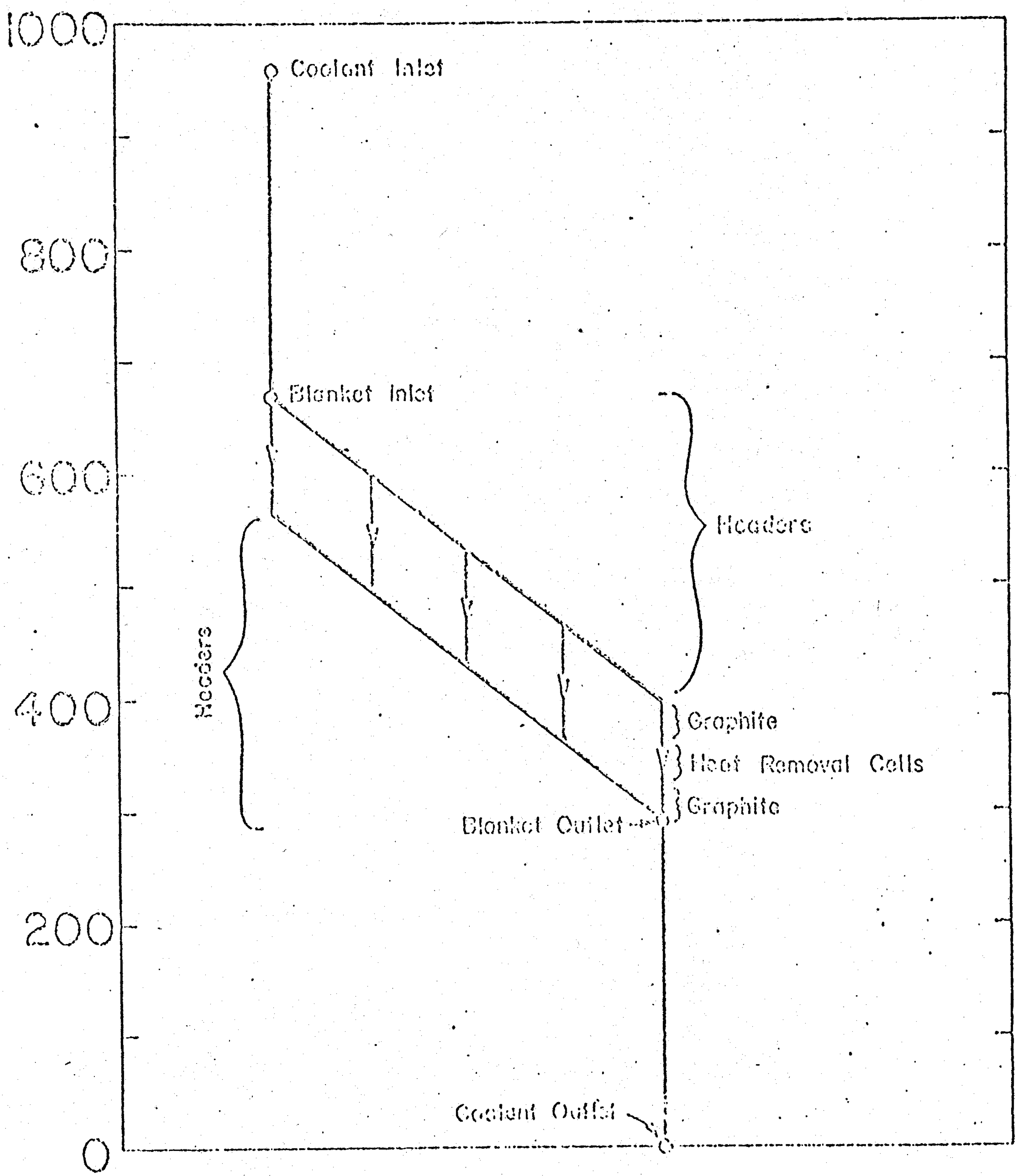


Fig. 3 Section Views of Blanket

Fig. 4 Coolant Pressure Distribution



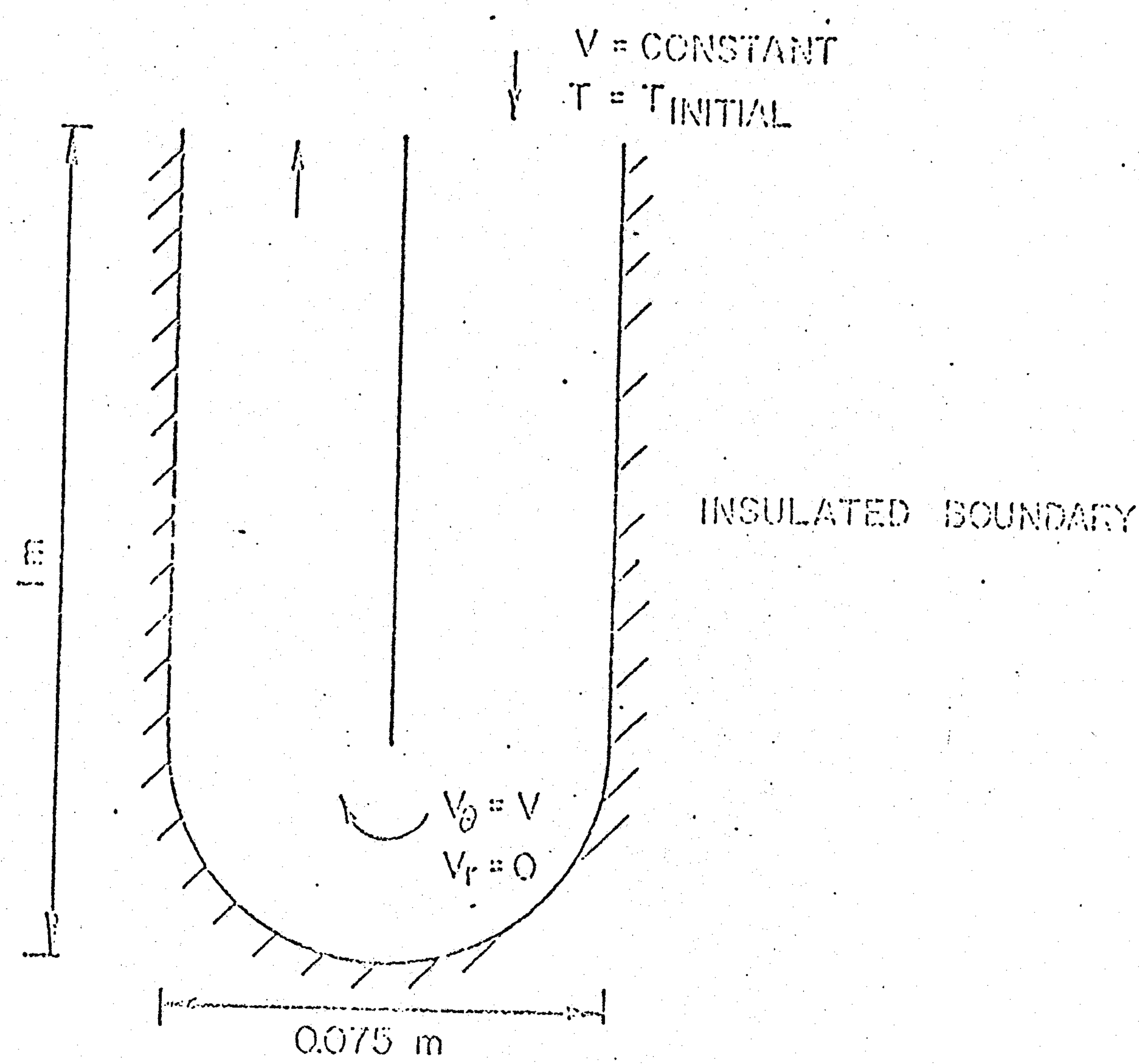
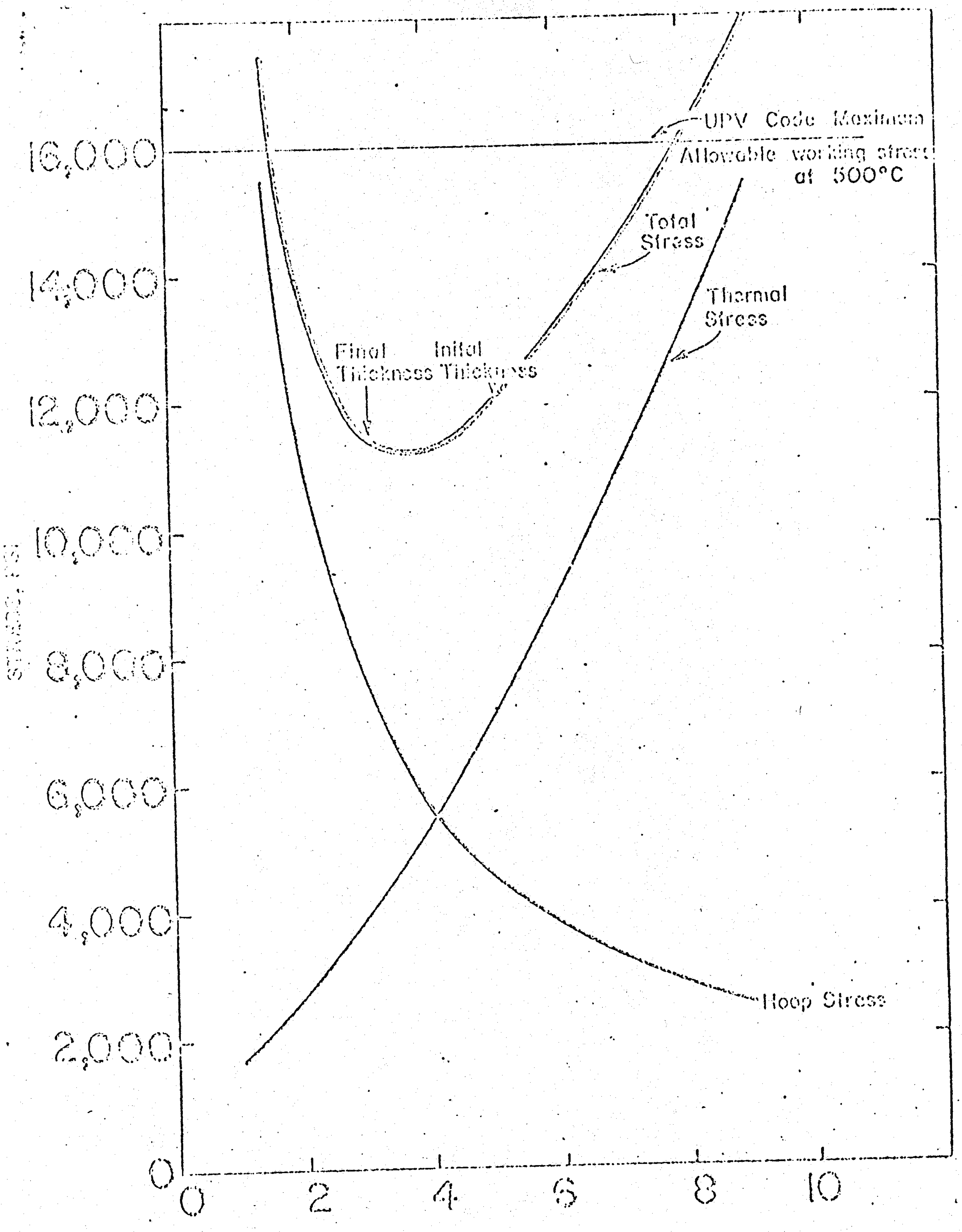


FIG. 5 MODEL FOR HEAT TRANSFER CALCULATIONS


UPV Code Maximum
Allowable working stress
at 500°C
Total
Stress
Thermal
Stress
Final
Thickness
Initial
Thickness
Hoop Stress
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
0
2
4
6
8
10