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by

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HELIUM COOLING OF A FUSION REACTOR BLANKET

N. E. 536 Jan. 1972 Bob Edwards

INTRODUCTION:

The motivation for looking into this subject are the advantages that helium cooling offer. The advantages are such that if it is at all possible to cool with helium, it seems like this would be the way to go. Five advantages were given in the references and they are listed below:

1. It is chemically inert and by itself does not produce a corrosion problem.

2. It is non-conducting and hence not affected by a magnetic field.

3. When pressurized, it has good heat transfer properties (mainly a high specific heat) and the technology of helium cooling is already under development in regard to fission reactors.

4. When coupled directly to a gas turbine, cycle efficiencies up to 50% seem possible.

5. It has a small neutron cross section and would not be activated when passing through the blanket.

There are, of course, some disadvantages with helium, but the one that must be considered first is the increase in volume of the blanket. If the volume increase isn't reasonable, there is no need to consider it further. It is the purpose of this report to present the findings of two groups for the volume increase of the blanket. The groups are;

. . G. R. Hopkins and G. Melese-d'Hospital, Direct Helium Cooling Cycle for a Fusion Reactor Blanket, presented at BNES Nuclear Fusion Conference at Culham Laboratory, Sept, 1969.

S. Förster and K. U. Schneider, Design Possibilites and Consequences for the Conventional Parts of Fusion Power Plants, presented at Symposium on Fusion Technology at Aachen, Sept 22-25 1970.

Their results show the additional volume needed for helium and associated tubing to be as small as 3.35% of the lithium volume for niobium as structural material.

Calculational Method for Additional Volume:

In calculating the additional volume needed to cool the blanket, the only consideration made here is from the heat transfer point of view. Nothing is done to consider the effect on the energy and spatial distribution of the neutrons and resulting effect on heat generation rate in the blanket. To get started , the energy deposition in the blanket has to be known. Assuming the helium has no effect on energy deposition, the heat generation rate is taken as that calculated by Steiner for a lithium blanket.

Immediately when one thinks about cooling something with a gas, you have to consider high pressures to keep the volume down. To contain the pressure with as little material as possible, you have to use small diameter tubing in the range of 1 to 3 cm, depending on the pressure.

The GGA report offers the only explanation of how to calculate the extra volume, and it will be the method described here. (The German design has a more complicated heat transfer problem to solve, and they didn't describe their method in the above reference.) The GGA people use cooling tubes which are parallel to the plasma as shown in figure 1. This simplifies solving the heat equation in that for a particular tube, the heat generation rate in the lithium along the length of the tube is taken as constant. For simplicity, the heat generation in the tube material is taken as that for the lithium in the blanket region. In the wall region, however, the heat generation rate in the tubes was taken as that for the wall material, as will be seen shortly.

There are many variables of importance to consider in solving the problem for the increased volume; pressure(p), cooling tube inside diameter(d), amount of material allowed for tubing, helium inlet and outlet temperatures, flow rate, etc. There are several ways of proceeding to make a parametric study of the combination of variables to give the minimum volume of helium needed. The GGA people varied the pressure and helium inlet temperature, but fixed the fractional volume of Nb in the tubing at an average value of 3.6% that of the total volume.

To start the problem, you must pin down a tube diameter and determine the volume of lithium that can be cooled per tube. To pin down a tube diameter consider a tube in the lithium region of the blanket near the first wall but not cooling the first wall as shown in figure 3. The t/d ratio where d is the inside diameter and t the thickness is gotten by specifying

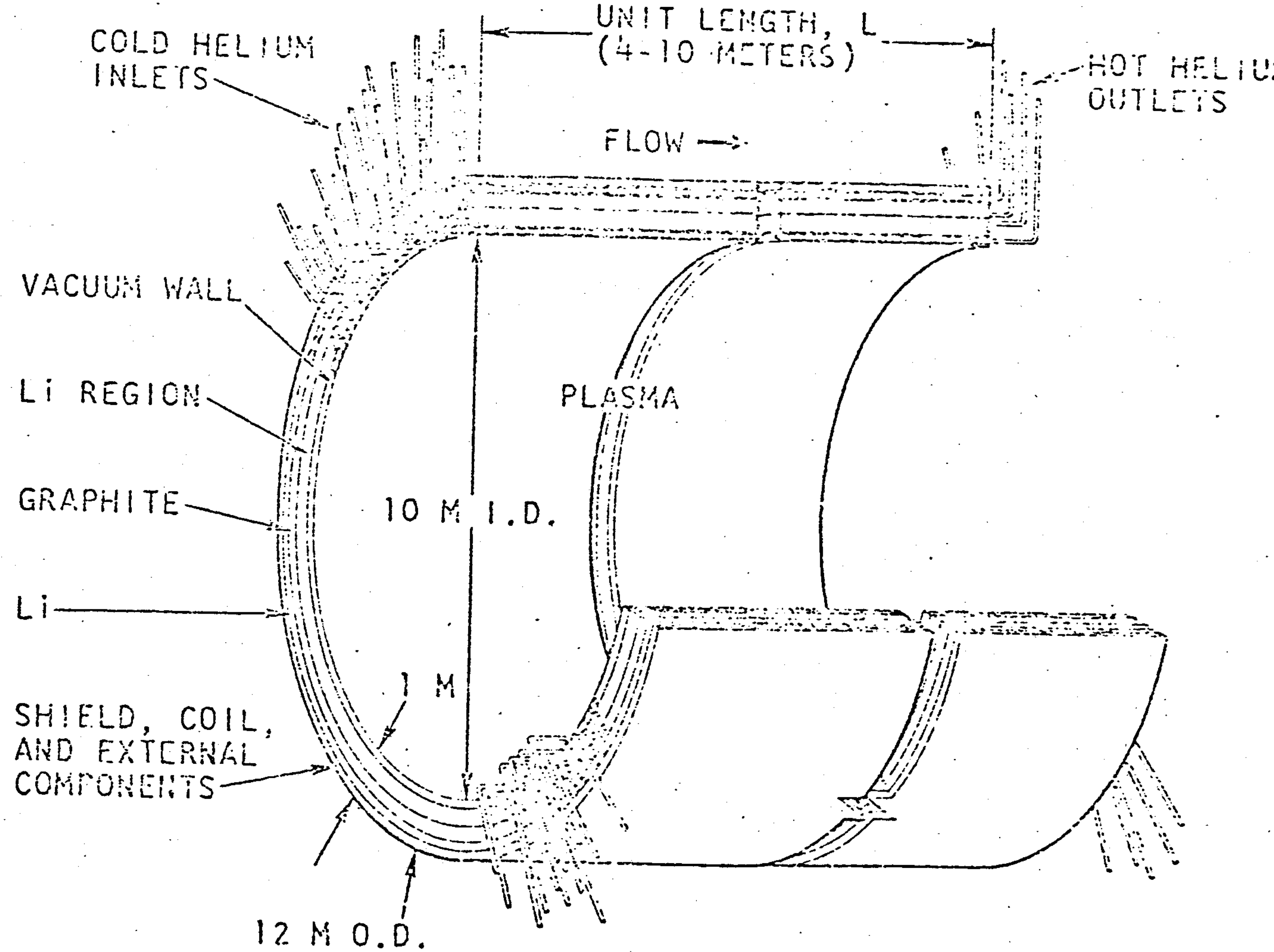

Fig.1 Proposed fusion reactor blanket.

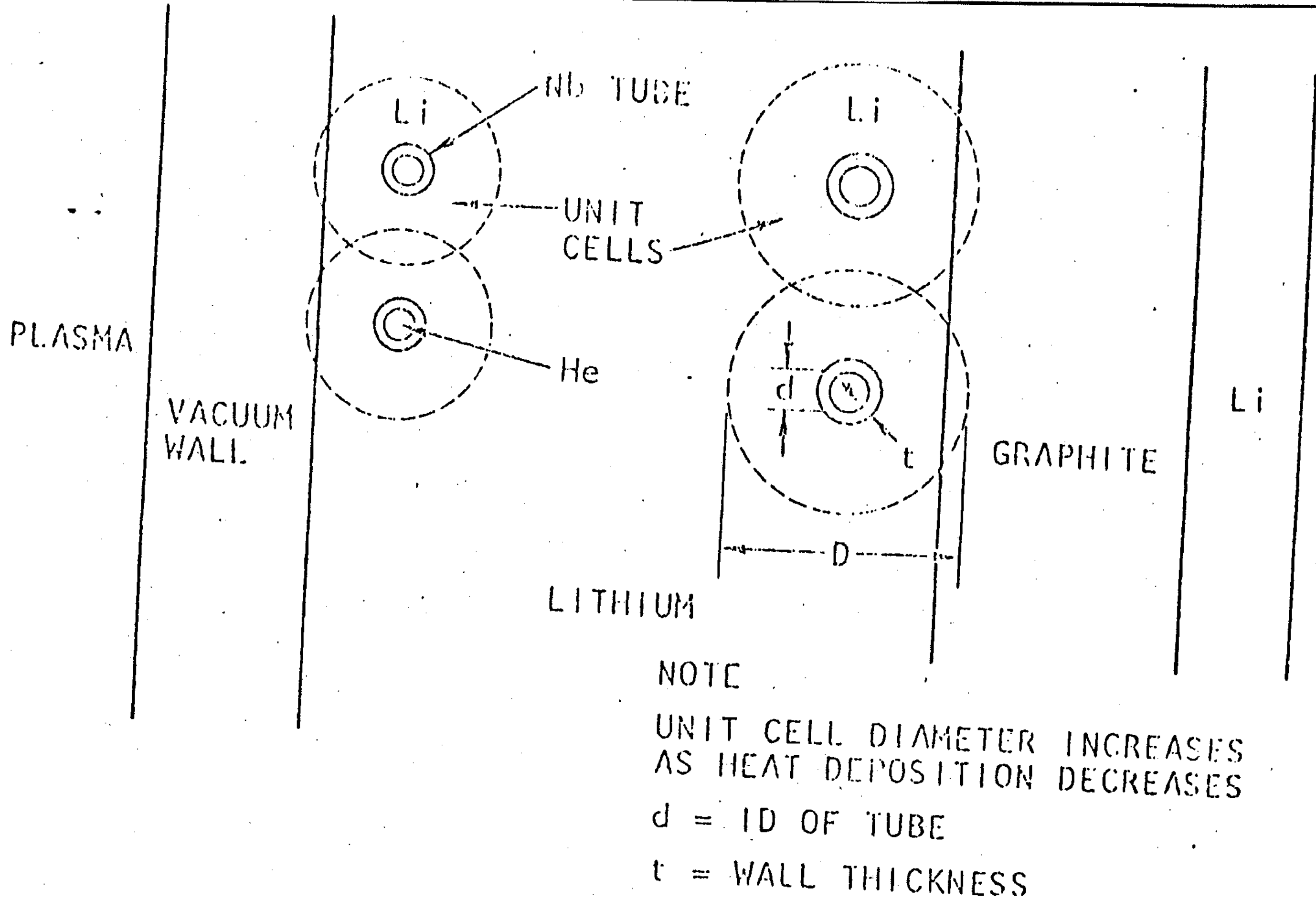

Fig.3 Cross section of blanket lithium region calculational model.

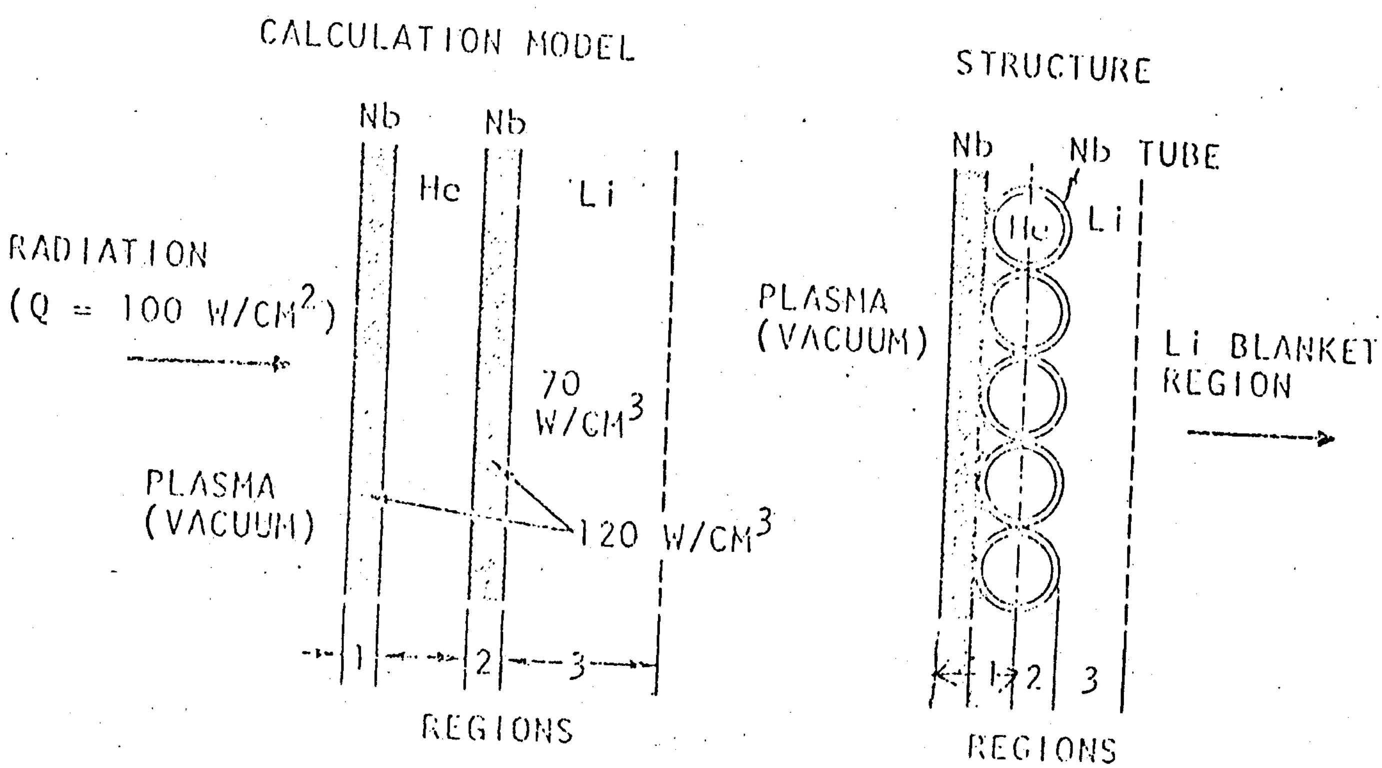

Fig.4 Cross section of vacuum wall model.

e pressure:

$t/d = p/2\sigma$ σ = alowable working stress (3500 psi was used by GGA, but the thermal stresses were calculated to be 500 psi, so that the tubes are actually stressed to 4000 psi.)

σ_{MAX} = aporoximately 10,000 psi so that there is a safety factor of 2.5

The question that you want to answer is how large a cell of diameter D can be cooled by this tube. Once D and d are known then the fractional volume of the cell which is helium is given simply by:

$$V = \frac{\text{volume of helium}}{\text{volume of helium} + \text{volume of lithium}} = d^2/D^2$$

Also, the fraction of the lithium plus niobium volume which is Nb can be defined:

$$X = \frac{\text{volume of Nb}}{\text{volume of Nb} + \text{volume of lithium}} = \frac{(d+2t)^2 - d^2}{D^2 - d^2}$$

Factoring the numerator gives:

$$X = \frac{4t(d+t)}{D^2 - d^2}$$

but, $d + t$ = aproximatelly d, so that this eqution can be solved for t/d also:

$$t/d = X(D^2 - d^2)/4d^2 = X(1-V)/4V$$

By limiting the value of X, then V can be calculated. Limiting the value of X at 5% for the tube being considered (in the lithium region near first wall where the heat generation rate is highest), will yield V for that cell.

By solving the heat equation an expression can be gotten for D in terms of V.

$q''' = -K_{Li}\nabla^2 T$ q''' = heat source

$$K_{Li} = 0.625 \text{ W/cm }^\circ C \text{ at } 1200^\circ C$$

In cylindrical geometry where the temperature depends only on r:

$$q''' = -K_{Li} \frac{1}{r} \frac{d}{dr} r \frac{dT}{dr}$$

$$rq''' = -K_{Li} \frac{d}{dr} r \frac{dT}{dr}$$

Integrating this equation over r once assuming q''' and K_{Li} are constant:

$$\frac{r^2}{2} q''' = -K_{Li}\, r \frac{dT}{dr} + C \qquad C = \text{constant of integration}$$

Assuming no heat transfer across the boundary of the cell, then at $r = D/2$, $\frac{dT}{dr} = 0$. Hence, $C = D^2 q'''/8$.

$$\frac{dT}{dr} = D^2 q'''/8K_{Li} r - q''' r/2K_{Li}$$

Integrating again and applying the following boundary conditions:

$T|_{d/2}$ = maximum Nb temperature (1200°C was used by GGA)

$T|_{D/2}$ = maximum Li temperature (1275°C was used by GGA)

yields:

$$\Delta T = D^2 q''' \ln(D/d)/8K_{Li} - q'''(D^2 - d^2)/16K_{Li}$$

$$\Delta T/D^2 = q'''(-\ln(d^2/D^2) - (D^2 - d^2)/D^2)/16K_{Li}$$

$$\Delta T/D^2 = q'''(V-1-\ln V)/16K_{Li}$$

Solving for D:

$$D = 4\sqrt{\frac{\Delta T\, K_{Li}}{q'''}}\,(V-1-\ln V)^{-\frac{1}{2}}$$

At this point we have V from before and D can be calculated from this equation. From D the tube diameter d is simply:

$$d = D\sqrt{V}$$

This ties down the tube diameter used in the blanket. The GGA people then used the same diameter tubes to calculate the number needed to cool the blanket and first wall as shown in figure 4. For the tubes further away from the wall, D gets larger as the heat generation rate is smaller. Thus V and X decrease radially also, and by determing the number of tubes needed in each region of the blanket V and X can be averaged.

So far only half the heat transfer problem has been solved, getting the heat from the Lithium to the inside surface of the tube. To get the heat into the helium requires another heat transfer equation based on forced convection of a gas and an experimentally determined heat transfer coefficient. The ability of the helium to remove the heat from the tube will determine the tube length and it is given by the following equation:

$$\frac{L}{d} = \frac{1}{4N_s} \frac{(T_{exit} - T_{inlet})}{(T_{Nb}^{max} - T_{exit})}$$

For the lithium region of the blanket T_{exit} was fixed at $1000^{o}C$ and the inlet temperature was also varied by GGA. N_s is the stanton number and is experimentally determined.

$$N_s = \frac{Nu}{Pr\ Re} = \frac{h}{\rho \cdot c \cdot U}$$

$$N_s = 3 \cdot 10^{-3} \text{ for GGA}$$

h = film coeficient
ρ = density
c = specific heat
U = flow velocity

To cool the first wall, GGA considered only a one dimensional problem as shown in figure 4. In region 1 is the first wall, half the tubing, and the Li between the tubes. In region 2 is just half the tubing. They found that to cool the first wall adequately required an inlet temperature of 100°C while the outlet temperature from the wall had to be only 750°C.

At this point all the equations needed to calculate the additional volume of helium are above, and the steps are summarized below:

1) Calculate t/d from the pressure.

2) Specify X^{max} and clculate V^{max} for the lithium region of the blanket.

3) Compute D^{min} from V^{max} and q'''_{max}

4) Calculate d from D^{MIN} and V^{max}.

5) Using the same diameter tubes determine D, V, and X for the other regions of the blanket.

6) Average X and V over the blanket.

GGA did this analysis for 3 pressures and 3 inlet temperatures and part of the results are summarized below:

pressure atm	20			30			50		
inlet temp °C	300	400	500	300	400	500	300	400	500
$V_{avg}(V_{max})$	0.14(0.273)			0.11(0.20)			0.075(0.14)		
d (t) cm	3.13(0.125)			2.27(0.136)			1.61(0.160)		
tube length cm	910	780	650	660	565	475	470	400	335
wall outlet temp °C	750	726	696	772	743	717	786	763	731
mixed mean outlet T °C	959	961	963	964	965	967	967	963	969
$\frac{\Delta p}{p}$ %	7.65	7.0	6.1	4.05	3.67	3.2	2.05	1.34	1.62
cycle efficiency %	35.4	41.0	43.8	38.7	44.0	47.0	40.6	45.3	43.4

Note: Cycle efficiency accounts for pumping power requirement.
X_{max} = 0.06 for all cases X_{avg} = approximately 0.036 for all cases

Note that the volume fraction of helium at 50 atm is 7.5%. If you wish to include the 3.6% for tubing then the additional volume needed is "approximately" 11.1%. I say approximately BECAUSE the 7.5% above is:

$$V = \frac{\text{Vol He}}{\text{Vol Blanket}}$$

, but to calculate the additional volume you need:

$$V' = \frac{\text{Vol He}}{\text{Vol Li}}$$

, likewise for X.

The correction necessarry can be gotten:

$$V = \frac{\text{Vol He}}{\text{Vol He} + \text{Vol Nb} + \text{Vol Li}} = \frac{1}{1 + \frac{\text{Vol Nb}}{\text{Vol He}} + \frac{\text{Vol Li}}{\text{Vol He}}}$$

$$V = \frac{1}{1 + \frac{4\pi d t}{\pi d^2} + \frac{1}{V'}}$$

, solving this for V'

$$\frac{1}{V'} = \frac{1}{V} - \frac{4t}{d} - 1 = \frac{1 - V - \cancel{\frac{4t}{d}V}}{V}$$

neglect as a second order term

$$V' = \frac{V}{1-V}$$

, likewise for X

$$X' = \frac{\text{Vol Nb}}{\text{Vol Li}} = \frac{X}{1-X}$$

Applying this to V = 7.5% and X = 3.6%, you get V' = 8.1% and X' = 3.75% and X' + V' = 11.8%.

The correction certainly isn't very large, but I introduced this point because for the German reactor design to be considered next, they tabulated values of V' and X' directly. In their design, they considered only one pressure (30 atm) and varied the coolant tube diameter, thus varying the volume fraction of Nb in the blanket. Their cooling scheme is also different, and apparently better, at least from the standpoint of heat transfer. They consider quasi-radial tubes as shown in the following figure.

The inlet tubes are curved to prevent neutron streaming, of course, but the tubes going out are curved for another reason. The tubes are curved primarily so that the heat generation rate along the length of the tube is such that the temperature of the tubing is kept at a maximum of 1000°C along the entire length. They probably won't be able to do this exactly, but they should be able to come pretty close. Their results depend on this assumption. The big advantage of this method is that more effective use is made of the coolant and less will be needed. In the GGA design the maximum tube temperature occurrs only at the outlet and thus much of that blanket is "overcooled". This is the explanation that I offer for the disproportinate drop in the coolant and coolant tube wall material volume fractions for the German design as can be seen in the following table.

They considered 90 atm pressure and varied the tube diameter between 0.5 cm to 2.5 cm. Of course, the smaller the tube diameter, the smaller $\overline{X}'$ will be, but they concluded that a tube diameter of 0.5 cm would result in having to make too many weld connections to the inlet tubes. They also considered a TZM alloy for the tube material which has a much higher working stress. They also used some different values for some of the parameters given below:

$T_{wall}^{max} = 1000°C$ $\quad$ $T_{exit} = 950°C$ $\quad$ $T_{inlet} = 513°C$

$T_{Li}^{max} = 1335°C$ $\quad$ $\sigma_{Nb} = 3400$ psi $\quad$ $\sigma_{TZM} = 11,100$ psi

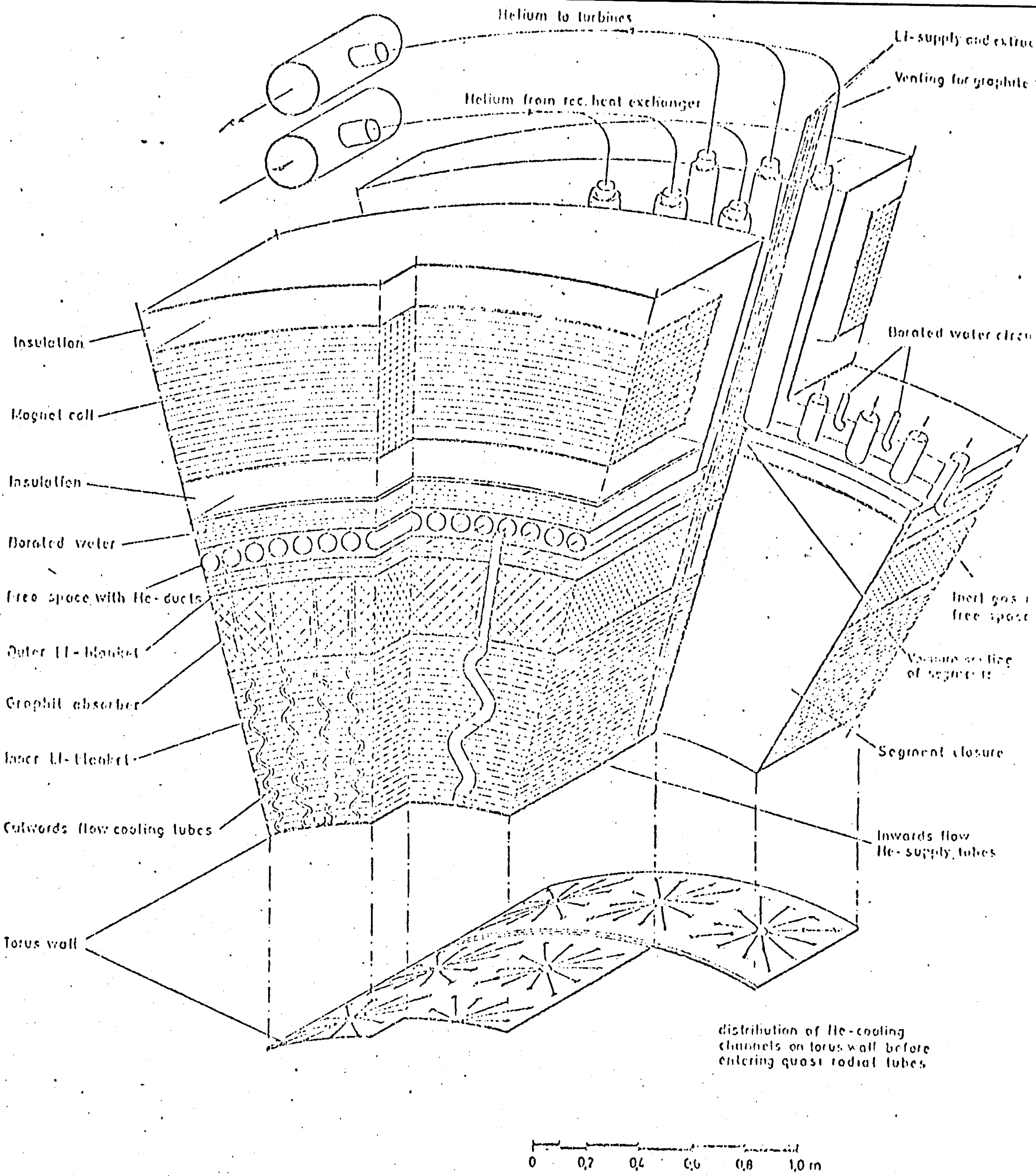

Fig. 6 Torus-type fusion reactor

Design of torus segments with blanket internals, sealing of segments and external He-gas ducts (corresponding to cycle 2, fig. 1, r_W = 1,5 m, cooling tube inner diameter 1 cm).

Choosing 1 cm as the tube diameter, they varied the allowable pressure drop in the blanket at 2.5, 5.0, and 7.5%. To do this they held the mass flow to the blanket fixed and varied the number of tubes and hence the flow velocity. The disadvantage of using fewer tubes is a higher friction pressure drop and this results in more pumping power and a lower plant efficiency.(but not much lower). The results are contained in the table below:

	without reheat						RECOMMENDED DESIGN ↓		reheat	
									HP	LP
$\frac{\Delta p}{p}$ %	2.5	5.0					7.5	5.0	5.0	
Torus tube radius Meters	← 1.5 →							2.0	1.5	
Net cycle efficiency %	47.6	46.8					46.0	46.8	49.9	
d cm	1.0	0.5	1.0	1.5	2.0	2.5	1.0	1.0	1.0	
diameter of inlet tubes cm	← 5.0 →									
suface area of exit tubes 1000 m^2 (includes graphite)	2.377	3.242	2.032	1.802	1.721	1.63[illegible]	1.359	2.041	2.429	3.177
length of exit tubes meters	1.625	1.078	1.625	2.172	2.936	3.599	1.625	1.625	1.546	1.431
length of inlet tubes meters	← 1.405 →									
number of exit tubes 1000	53.01	175.3	34.49	16.22	8.37[illegible]	5.63[illegible]	30.61	37.65	50.0	65.40
number of inlet tubes 1000	← 3.165 →									
X' + V' for Nb AVERAGE %	4.42	3.15	3.57	4.49	5.24	6.03	3.35	3.92	6.21	
X' + V' for TZM AVERAGE %	3.54	2.73	2.99	3.59	4.05	4.57	2.97	3.25	5.24	
X' + V' + S' for Nb AVERAGE %	3.95	7.50	3.03	3.71	9.67	10.52	7.60	3.03	20.55	
X' + V' + S' for TZM AVERAGE %	7.[illegible]8	7.11	7.34	7.3[illegible]	3.45	3.9[illegible]	7.03	7.21	13.95	

NOTE:

$t_{Nb} = 0.2\ d \qquad t_{TZM} = 0.06\ d$

The length of the tubes in the non-Lithium region is approximately 30 cm. (GRAPHITE)

The power produced by this reactor using Steiner's results is a factor of 1.3 above the assumed power of 5000 MW.

For the 1 cm tube diameter, they concluded that a 46 % efficiency was good enough for the 7.5% pressure drop in the blanket, which gives the lowest value of the volume fraction of tube material and coolant (X' + V') of 3.35% for Nb and 2.37% for TZM. They also considered the volume fraction of structure besides tubing, S', and included that in their table.

CONCLUSION:

Using high pressure helium to cool the blanket radially results in very small aditional volume of the blanket, <3.5% for coolant and tubing. This would seem to be a tolerable increase in blanket volume, but whether or not it is a practicle method from the standpoint of fabricability and cost remains to be seen.