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THERMAL ANALYSIS OF A HELIUM-COOLED, TUBE-BANK BLANKET MODULE FOR A TANDEM-MIRROR FUSION REACTOR*

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ABSTRACT

A blanket module concept for the central cell of a tandem mirror reactor is described which takes advantage of the excellent heat transfer and low pressure drop characteristics of tube banks in cross-flow. The blanket employs solid Li_2O as the tritium breeding material and helium as the coolant. The lithium oxide is contained in tubes arranged within the submodules as a two-pass, cross-flow heat exchanger. Primarily, the heat transfer and thermal-hydraulic aspects of the blanket design study are described in this paper. In particular, the analytical model used for selection of the best tube-bank design parameters is discussed in some detail.

NOMENCLATURE

A	=	area
A_c	=	flow channel total cross-sectional area
C_p	=	specific heat of helium
d_h	=	diameter of the He purge hole in the Li_2O
d_i	=	inner diameter of the tube
d_L	=	diameter of the Li_2O cartridge
d_o	=	outer diameter of the tube
D_H	=	hydraulic diameter
f_L	=	fraction of Li_2O in the tube bank
f_s	=	fraction of structure in the tube bank
f_{TD}	=	fraction of 100% theoretical density of the Li_2O
f_v	=	total "void" fraction in the tube bank
G	=	mass flux, ρv
h	=	average convective heat transfer coefficient
k	=	thermal conductivity of helium
k_L	=	thermal conductivity of Li_2O
k_w	=	thermal conductivity of the tube wall
$\dot{m}$	=	mass flow rate
Nu	=	Nusselt number
P	=	pressure
Pr	=	Prandtl number
Q	=	heat flow or input
q	=	heat flux
r	=	radius measured from the first wall at the Canister separation point
r_L^*	=	decay length for internal heat generation in Li_2O
r_s^*	=	decay length for internal heat generation in the tube material
Re	=	Reynolds number, GD_H/μ
s	=	path length along the flow in the canister
s_t	=	transverse stagger of the tube bank
s_l	=	longitudinal stagger of the tube bank
t	=	thickness of the first wall
t_g	=	annular gap for helium purge flow
t_L	=	thickness of the Li_2O annular cartridge
t_s	=	width of the minimum spacing between tubes
t_w	=	thickness of the tube wall
T	=	temperature
T_B	=	bulk mean temperature of the helium
T_w	=	wall temperature
v	=	velocity
V	=	volume
w	=	internal heat generation
$w_{o,L}$	=	internal heat generation in the Li_2O at $r = 0$
$w_{o,s}$	=	internal heat generation in the structure at $r = 0$
ζ_t	=	geometrical parameter defined by Eq. (13)

GENERAL DESCRIPTION

The Lithium Oxide Canister Blanket is central to the fusion reactor engineering system used for translating fusion neutron kinetic energy to a more useful form, i.e., thermal energy, which may then be used in the production of portable fuels such as hydrogen(1) or for the production of electricity, or both. Figure 1 relates the Canister blanket to the tandem mirror reactor. Many previous studies contributed to our

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understanding of helium-cooled blankets and the use of solid lithium compounds. References 2 and 3 had a particularly important influence on our design concept.

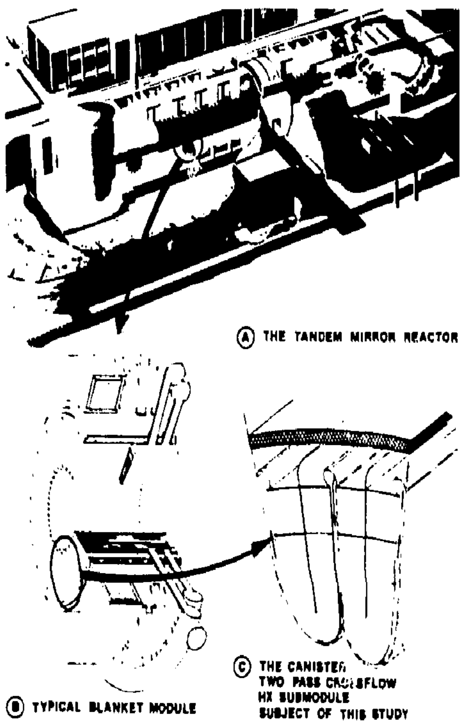

FIG. 1 RELATIONSHIP OF THE BLANKET MODULE TO THE REACTOR

In addition to the neutron moderation and energy conversion the blanket must also produce tritium for the reactor fuel cycle via neutron reactions with lithium. Implicit in this tritium production are two requirements: 1) means must be provided for recovering the tritium and delivering it where it is needed; and 2) the tritium inventory in the blanket and in the tritium loop must be kept at as low a level as possible for reasons of safety. A typical target for the tritium inventory level in the blanket is of the order of 1 kilogram for a reactor producing 3000-4000 MW of fusion power. In this design we are well below the 1-kilogram target.

In this particular Canister blanket we have elected to use a combination of lithium oxide as the moderator and helium as the coolant in the belief that gas-cooled "dry" blankets offer distinct advantages of simplicity, safety and ease of startup and shutdown over those blankets using some combination of water, liquid metals and/or molten salts. We also use "in situ" tritium control rather than slip stream processing to assure that our hydrogen product is tritium free. In situ tritium control isolates the tritium from the main helium flow. Recovery of the tritium is by an independent purge circuit.

The four candidate structural materials we examined were 316 SS, 2-1/4 Cr - 1 Mo, Inconel and Tenelon. The structural material selected for the blanket is Tenelon (a steel using manganese instead of nickel), chosen for its low residual radioactivity. The waste disposal rating (WDR) of Tenelon is 0.40, which means that Tenelon has 40% of the NRC curies per m^3 allowed for near-surface disposal of spent blankets; that is, deep burial is not required. Tenelon also has very attractive neutronic performance and structural properties and is selected as our reference material.

The physics base for the energy-producing central cell of the TMR is described fully in Ref. 1. For purposes of the blanket design, the central cell is characterized by the parameters listed in Table 1 and illustrated in Fig. 2. Note that the first-wall radius is fixed by the specified neutron wall loading of 2.0, while the much smaller plasma radius is fixed by the plasma physics requirements.[1]

TABLE 1 PARAMETERS FOR THE CENTRAL CELL NEEDED FOR BLANKET DESIGN

Central cell nominal length, L	150 m
Number of solenoidal coils	38
Spacing between successive solenoidal coils, l	4 m
Coil I.D., including all structure, coolant circuit, shielding, etc.	6.3 m
Coil O.D.	10.3 m
Coil width, w	1.0 m
Coil height, h	2.0 m
Clear space between coils axially	3.0 m
Plasma radius, r	0.6 m
First wall radius, r_w	1.49 m
Fusion power, P_f	3500 MW
Average neutron wall loading, Γ	2.0 [illegible]

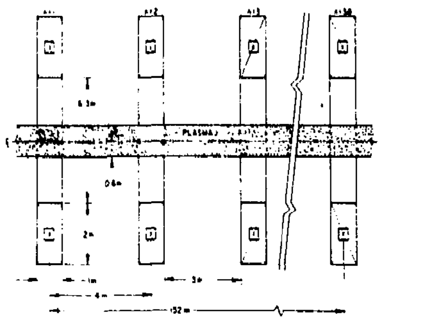

FIG. 2 CROSS SECTION THROUGH THE FUSION REACTOR CENTRAL CELL SHOWING PRINCIPAL DIMENSIONS

The blanket assembly must be physically located outside of the plasma region and within the bore of the solenoidal coils. The distance from the coils is determined by clearances for assembly. It is also an established convention to divide the total blanket into a series of axial modules and circumferential submodules. The axial length of a blanket module has been chosen to be half the distance between successive solenoidal coils. This allows us to leave the coils in place when blanket installation or removal is required. This is a highly practical consideration and one adopted here since the superconducting solenoidal coils and all their associated circuitry are generally designed for the life of the plant (∿ 30 years), whereas blanket module life expectancy is limited to approximately 3 to 5 years.

Figure 3 illustrates, in a highly schematic way, the principle of module placement or removal. Module A, shown in place, is installed by a vertical motion to the reactor center-line, followed by an axial translation placing it partially under the solenoid. Module B, a mirror image of A, is shown partially installed and need only be lowered to the reactor center-line to be in place. Structural supports between the fixed solenoidal coils are spaced so that vertical placement or removal of the blanket can be accommodated. Ring manifold piping is separately installed after the ring module is in place. The central cell is filled with 75 ring modules arranged in series axially along the 150-m central cell. The ring module is illustrated in Fig. 1.

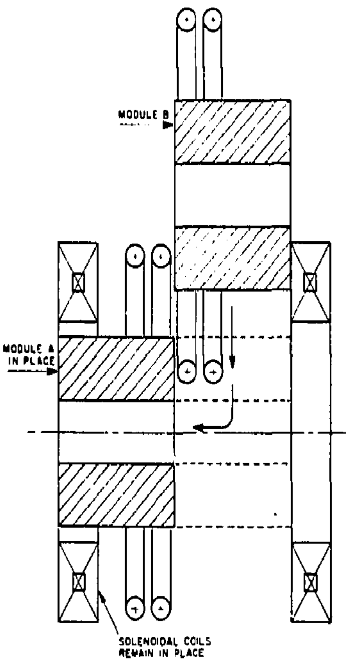

FIG. 3 METHOD OF MODULE REMOVAL FROM THE CENTRAL CELL OF THE TMR

DESCRIPTION OF THE CANISTERS

The individual submodules of the ring modules are designated as Canisters. The bulk of the blanket design focuses on these Canisters. The number of Canisters within the ring module is not an arbitrary choice but is dictated by considerations of thermal and hoop stress since the Canister is a pressure vessel. We have chosen to use 18 Canisters within the ring module. These Canisters are further divided into mirror-image halves to reduce stresses.

A cross section through a Canister is shown in Fig. 4. The Canister as a unit consists of:

a) A relatively cool pressure vessel or container.
b) The assembly of lithium-oxide-filled tubes in the container.
c) A hot shield of solid metallic rods.
d) A plenum section in which flow manifolding is accommodated.
e) A cold shield that acts as the outer ring section of the Canister pressure vessel.
f) Piping couplings penetrating the cold shield and leading to the ring manifolds.

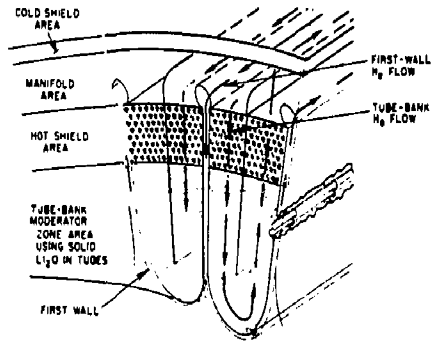

FIG. 4 CROSS SECTION THROUGH ONE CANISTER OF A BLANKET MODULE

The moderator zone is comprised of an assembly of tubes across which the helium coolant is caused to flow. The tubes are on a closely spaced triangular pitch. The assembly of tubes constitutes a two-pass, cross-flow heat exchanger. In this moderating section the tubes are filled with lithium oxide "cartridges" designed in the form of half washers, split rings or short cylinders. The advantage of using one of these general shapes is that the cartridges are "pre-cracked" both axially and radially and thermal stress problems can be minimized. They can be readily loaded into a long tube, and fabrication with good dimensional tolerance should not be difficult. The density of the lithium oxide can also be precisely controlled.

A sub-assembly of the Canister is thus a long tube (∼ 2 m) within which the lithium oxide resides. The tube protects the oxide from the mainstream helium coolant so that it does not tend to disintegrate due to the high velocity flow; the tube also protects it from trace-contaminant action. Most importantly the sub-assembly also provides in situ first-line tritium control, as illustrated in Fig. 5. Tritium control is discussed in detail in Ref. 1.

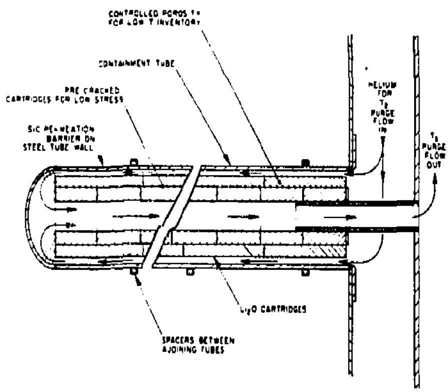

FIG. 5 "IN-SITU TRITIUM CONTROL" IN ONE TUBE OF THE CANISTER TUBE-BANK USING A SMALL PURGE HELIUM FLOW TO COLLECT THE TRITIUM

Briefly, however, the matrix of lithium-oxide-filled tubes is mounted in a tube sheet. The tube sheet is at one end only of the Canister and is oriented normal to the mainstream helium coolant flow. Purge helium, totally separated from the main helium flow but at only slightly lower pressure, flows first in the annular space between the tube wall and the Li_2O cartridge and then returns through the central hole in the cartridge. The mass flow of this helium used to purge the tritium is very low and inconsequential compared to the mainstream coolant flow.

In the hot shield zone of the Canister the tubes are replaced by solid rods. In the cases that were studied for the Canister thermal-hydraulic performance, all tubes and rods were assumed to be the same diameter. This need not be the case nor is it necessary to have all moderating tubes the same diameter. In fact, tubes could progressively increase in diameter as a function of increasing blanket radius to partially compensate for the exponentially decreasing energy deposition. For this particular study we concentrated mainly on sizing the tubes to match overall neutronics/thermal-hydraulic needs and have not as yet used the second order refinement of having graded sizes.

THE CANISTER FIRST WALL AND STRUCTURAL ENVELOPE --THE COOL CONTAINER

The Canister structural container is an independently cooled, double-walled envelope surrounding the lithium-oxide-moderating medium and the hot shield. The coolant circuit for the first wall is shown in Fig. 4. To optimize the interfacing of the overall reactor blanket modules with the thermochemical plant (see Ref. 1 for details), the following specific design parameters were chosen for the Canister-wall coolant circuit:

- o Coolant - helium
- o Inlet temperature, $T_{BIN} = 525$ K
- o Outlet temperature, $T_{BOUT} = 625$ K
- o Coolant pressure, P = 50 atm
- o First wall is independently and integrally cooled
- o A quasi-adiabatic surface is assumed to exist between the first wall coolant circuit and the main body of the moderating blanket
- o Wall thickness = 0.006 m

With these data and one further simplifying approximation, it is possible to closely estimate the maximum material temperature in the first wall. The approximation is that all energy deposition occurs in the curved surface of the first wall of length, $\ell = 0.13 \times \pi = 0.41$ m, and that essentially no energy deposition takes place in the lead-in and lead-out lengths. The annular 2 mm spacing, δ, between the first wall and the adiabatic surface forms the cooling channel. This channel is kept intentionally small to enhance heat transfer. The hydraulic diameter of this channel is 2 δ.

The maximum material temperature is based on a first-wall energy deposition of 45.1 kW per meter of first wall in the axial (B field) direction. The average helium flow velocity of 10.18 m/s leads to an average Nusselt number of 20.3 and a film drop of 93 K. The temperature drop across the first is 13 K. The upper limit on the first wall material temperature is thus:

$$T_{MAX} = T_{B(OUT)} + \Delta T_{FILM} + \Delta T_{WALL} \approx 625 + 93 + 13 \approx 731 \text{ K} \quad (1)$$

The film temperature drop of 93 K is somewhat high but acceptable since the material temperature of 731 K is well below a design limit of 823 K imposed by radiation damage considerations and low enough to be below the creep stress regime. The stress analysis is described in detail in Ref. 1.

Table 2 lists the significant set of numerical values for the Canister envelope and first wall structure. The principal features of the design can be summarized as follows:

a) The Canister structural envelope is purposely designed to run cooler than the blanket elements inside it; the maximum envelope temperature of only about 731 K is maintained this low by a separate helium coolant circuit.

b) The relatively cool structural temperature allows the Canister envelope to serve as a pressure vessel for the 5 MPa helium coolant flowing through the blanket tube bank.

c) The combined hoop and thermal stress in the first wall is only about half the yield stress of the Tenelon alloy selected when the neutron wall loading is 2.0 MW/m^2.

d) The fractional pressure drop in the first-wall helium coolant is only about 0.10%, resulting in a very small ratio of pumping power required to thermal power removed of only 0.17%.

e) The "cool container" concept allows great flexibility in the design of the Canister itself as well as the design of the tube-bank breeder blanket and hot shield inside it.

f) There appears to be sufficient strength of the Tenelon to allow moving the Canisters closer to the plasma up to a neutron wall loading of almost 5 MW/m^2. This has the possible advantage of decreasing the size and cost of the blanket and central cell magnet coils (at the expense of much shorter blanket lifetimes).

TABLE 2 THE CANISTER STRUCTURAL ENVELOPE AND FIRST WALL DATA SUMMARY

<u>Neutronics of Plasma Heat Loads</u>	
Design neutron wall loading, Γ_N	2 MW/m^2
Possible max. neutron wall loading	5 MW/m^2
Volumetric heat generation	18.34 MW/m^3 for $\Gamma_N = 2.0$
Incident charged particle flux to FW	2×10^4 W/m^2
<u>Structural</u>	
Plate thickness, first wall	0.006 m
Material	Tenelon
Maximum material temperature	731 K
Maximum combined stress	136 MPa
Minimum yield stress, Tenelon at 730 K	225 MPa
<u>Thermal-Hydraulics of First Wall Flow</u>	
Coolant medium	Helium
Pressure	5 MPa
Inlet temperature	525 K
Outlet temperature	625 K
Reynolds No.	5676
Nusselt No.	20.3
Flow velocity	10.18 m/s
Pressure drop	5158 Pa (< 1.0 psi)
Pumping power/half Canister	210 W
Power removed by first-wall coolant per half Canister	0.12 MW
% pumping power in cooling the first wall	0.17%

ANALYTICAL MODEL FOR THE HEAT TRANSFER IN THE CANISTER VOLUME

Early calculations in our first model of the

Canister blanket indicated that it would be difficult to obtain a relatively large rise in the bulk coolant temperature (say 300 or 400 K) as the coolant flows across the lithium-oxide-filled tubes. The reason for the difficulty was the short travel distance, h, of the coolant in this first model of the Canister initially designed as a single pass heat exchanger. As a single pass system the thermal-hydraulics were characterized by very low flow velocities, poor film coefficients of heat transfer, larger centerline temperatures in the lithium oxide than would be manageable, and higher tube temperatures than could be tolerated. Furthermore, in this first model the first wall was not independently cooled. To improve the thermal-hydraulics and to provide separate coolant circuitry, a two-pass heat exchanger was adopted as shown in Fig. 4. The calculational model for the blanket heat transfer may be described as a staggered tube, triangular pitch, crossflow heat exchanger. The dimensional parameters for the tubes and rods in this heat exchanger are shown in Fig. 6.

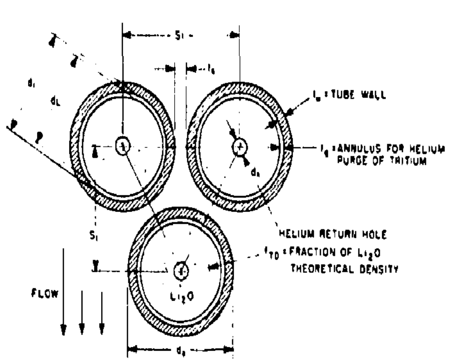

FIG. 6 UNIT CELL FOR THE TUBE BANK EMPLOYING ROUND TUBES

A very important parameter influencing the thermal-hydraulics of the blanket is the fraction of Li_2O that can be contained within the volume. Neutronically this fraction has to have a certain minimum value to assure adequate tritium breeding for a given radial depth of the moderator. Since the Li_2O is within the heat exchanger tubes, the tube diameters and the spacing between tubes are very important. The following equation allows this fraction of Li_2O to be calculated:

$$f_L = \frac{\pi f_{TD}}{2} \left[\frac{\left(d_i - 2t_g\right)^2 - d_h^2}{s_t^2 \tan 60^0} \right] \qquad (2)$$

Refer to Fig. 6 and the nomenclature for the definitions of the symbols.

The fraction that is structure is determined by the following equation:

$$f_s = \frac{\pi}{2} \left[\frac{d_o^2 - d_i^2}{s_t^2 \tan 60^0} \right] \qquad (3)$$

The heat transfer in flow over tubes in crossflow depends to a large extent on flow pattern, degree of turbulence, velocity of the coolant, size and arrangement of tubes, entrance effects, first row effects, numbers of rows and columns, and on side wall geometry. For our particular situation the energy deposition per unit volume falls off by about a factor of 20 from the first wall region to the back of the blanket. A built-in advantage of the two-pass heat exchanger concept is that flow enters at channel 1 (see Fig. 7) where the hot shield rods are located. Here the power density and hence heat transfer is least. Thus, entrance effects on film coefficients are not of any consequence. Thereafter the flow across the continuously packed tubes, where power density is highest, is beyond the influence of entrance effects. As a result, we can use an average heat transfer coefficient, h, for the entire tube bundle as an excellent first approximation.

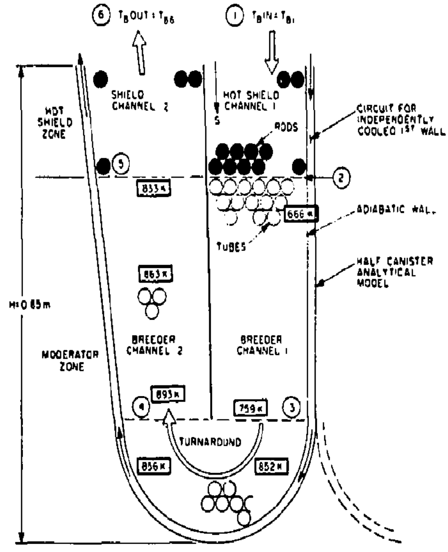

FIG. 7 CROSS SECTION THROUGH THE CANISTER WITH NUMBERING FOR THE THERMAL-HYDRAULIC ANALYSIS OF THE TUBE BANK REGIONS

Figure 7 shows the path of the helium flow through the left half of the Canister as a two-pass heat exchanger. Figure 8 illustrates the local power density in the Canister for the numbered flow locations.

The assumptions used in developing the computer model are as follows:

a) The power density has the form $w = w_0 e^{-r/r^*}$ for each pass, where r is measured from the first wall region.
b) Negligible effect of turnarounds on temperature profiles.
c) Constant tube diameter of the staggered array.
d) Thermal isolation of the hot shield and moderator region from the internal manifolds and first wall regions.
e) f_s is that fraction of structure within the first wall envelope but not including the first wall itself.
f) The total "void" fraction for a unit cell (Fig. 6) is: $f_v = 1 - f_s - f_L$.

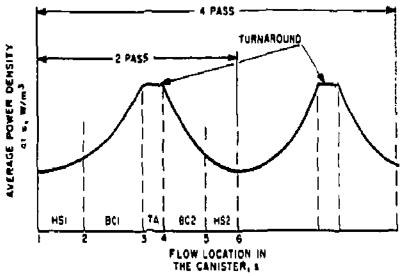

FIG. 8 PROFILE OF THE LOCAL POWER DENSITY IN THE CANISTER ALONG THE HELIUM FLOW PATH

The computer code uses the following equations in integral form in a zone-by-zone progression starting with the hot shield then through the moderator, turnaround, etc. The bulk coolant (helium) temperature rise is given by

$$dT_B(s) = \frac{dQ(r)}{\dot{m}\ c_p} \qquad (4)$$

Note that the length s is in the direction of the flow while r is radially outward.

The total heat deposited, dQ(r), over increment ds is

$$\begin{aligned} dQ(r) &= w_L(r)dV_L(r) + w_s(r)dV_s(r) \\ &= (w_L f_L + w_s f_s)A_c(r)ds \end{aligned} \qquad (5)$$

where dV_L and dV_s are the differential volumes of Li_2O and structure, respectively. The variables, f_L, f_s are the volume fractionsof Li_2O and structure in a unit cell. The variable A_c is the total channel cross-sectional area.

For the internal heat generation in the lithium and the structure, respectively,

$$w_L = w_{0,L}\ \exp\left(-\frac{r}{r_L^*}\right) \qquad (6a)$$

$$w_s = w_{0,s}\ \exp\left(-\frac{r}{r_s^*}\right) \qquad (6b)$$

and, therefore, for all regions except the turnaround zone:

$$\frac{dT_B}{ds} = \frac{\left[(w_{0,L}f_L\ \exp(-r/r_L^*) + w_{0,s}f_s\ \exp(-r/r_s^*)\right]A_c(r)}{\dot{m}\ c_p} \qquad (7)$$

The annular gap, t_g, between the tube wall and the Li_2O cartridge is provided for helium purge flow to scavenge tritium from the Li_2O. Its width vs the radial location r is specified by the linear relation

$$t_g(r) = B_1 + B_2 r \qquad (8)$$

where B_1 and B_2 are coefficients defined for each blanket region.

The diameter of the hole in the Li_2O, d_h, is chosen to give one half the flow area of the annulus,

$$d_h \simeq \sqrt{2t_g(d_o - 2t_w - t_g)} \qquad (9)$$

The hole diameter and the Li_2O thickness are based on the average gap in each region, $\bar{t}_g$, in order to guarantee a linear variation in the Li_2O volume fraction.

The Li_2O volume fraction vs the radial location r is specified by:

$$f_L(r) = B_3 + B_4 r \qquad (10)$$

where

$$B_3 = 4\varepsilon_t\left(\frac{t_L}{d_o}\right)\left(1 - \frac{2t_w}{d_o} - \frac{t_L}{d_o} - \frac{2B_1}{d_o}\right) \qquad (11)$$

$$B_4 = 4\varepsilon_t\left(\frac{t_L}{d_o}\right)\left(-\frac{2B_2}{d_o}\right) \qquad (12)$$

$$\varepsilon_t = \frac{\pi}{2\sqrt{3}\left(1 + \frac{t_s}{d_o}\right)^2} \qquad (13)$$

Since the structural volume fraction, f_s, is constant, the helium (void) volume fraction, f_v, also varies linearly.

To allow simple channel area changes, the channel cross section area vs the radial distance r is defined by the linear relation

$$A_c(r) = B_5 + B_6 r \qquad (14)$$

where the coefficients B_5 and B_6 are defined for each blanket region.

Integrating Eq. (4) with the linear relations for channel area (14) and Li_2O volume fraction (10) over the length of each successive region (except for the turnaround zone) gives the bulk He temperature rise for each of these blanket regions. (See Ref. 1 for the integral relations.)

For the turnaround zone, the relatively simple, approximate integral relation is

$$\Delta T_{B(TA)} = \frac{\left\{w_{0,L}f_L\left[1 - \exp\left(\frac{-\bar{r}_{TA}}{r_L^*}\right)\right] + w_{0,s}f_s\left[1 - \exp\left(\frac{-\bar{r}_{TA}}{r_s^*}\right)\right]\right\}A_{TA}\Delta S_{TA}}{\dot{m}\ c_p} \qquad (15)$$

The average ΔT_{film} between the local bulk temperature and the tube wall is inversely proportional to the average heat transfer coefficient, $\bar{h}$. The average heat transfer coefficient for turbulent flow in a cross flow multi-tube heat exchanger of 10 tube rows or more is given by the correlation[4]:

$$\frac{\bar{h}d_o}{k} = 0.33C_H(Re)^{0.6}(Pr)^{1/3} \qquad (16)$$

$$(Re > 6000,\ 0.7 < Pr < 300)$$

In our actual Canister model the number of tube rows is always greater than 10, satisfying the correlation equation, but the number of tubes in each row varies between 3 and 6. The correlation equation for $\bar{h}$ was developed assuming quasi-infinite row lengths so the effects of any end walls on the value of $\bar{h}$ would be negligible. In our design study, because of the small number of tube columns, the walls at the end of the tube rows could significantly effect the $\bar{h}$. Obviously any actual design would have to be supported with experimental measurements with similar geometries. We would also note that flow in the turnaround section of the Canister with the main flow turning 180° may not provide the flow conditions which give an h defined by Eq. (16).

The average film temperature drop in the helium from the bulk flow to the tube wall O.D. relative to the average heat transfer coefficient is

$$\Delta T_{film}(r) = \frac{q}{\bar{h}} \qquad (17)$$

where the surface heat flux, q, is determined from

$$q = \frac{w_L V_L + w_s V_s}{A_{tube}} = \frac{w_L f_L + w_s f_s}{4\varepsilon_t / d_o} \qquad (18)$$

The temperature rise across the tube wall is determined by combining the contribution due to the local power generation in the tube wall with the contribution due to the heat flux from the Li_2O traversing the tube wall. The final equation assuming axisymmetric heat conduction is:

$$\Delta T_{wall} = \frac{w_s \left(\frac{d_o}{2}\right)^2 \left[1 - \left(\frac{d_i}{d_o}\right)^2 + 2\left(\frac{d_i}{d_o}\right)^2 \ln\left(\frac{d_i}{d_o}\right)\right]}{4k_w} + \frac{w_L f_L \sqrt{3}(d_o + t_s)^2 \ln\left(\frac{d_i}{d_o}\right)}{4\pi k_w} \qquad (19)$$

The temperature drop across the internal helium gap (the annulus provided for tritium purge) can be determined assuming pure radial conduction in the helium and essentially zero velocity flow using the equation

$$\Delta T_g = \frac{w_L f_L \left[\ln\left(\frac{d_o - 2t_w}{d_o - 2t_w - 2t_g}\right)\right] \sqrt{3}\,(d_o + t_s)^2}{4\pi k} \qquad (20)$$

The mass flow of the purge gas is a small fraction of the mainstream flow, i.e., 0.1%. The largest mainstream flow for ΔT_B = 100 K would be ~ 6500 kg/sec. For the base case with 75 modules of 18 Canisters each and about 600 tubes per Canister, the flow in the annulus of one tube is about 8 mg/sec. This flow is so slow as to preclude significant heat removal by the purge flow.

To check the possibility of enhanced heat transfer rate caused by circumferential natural convection loops set up around the annulus, the Grashof number, $Gr = \rho g \beta \Delta T_g t_g^3/\mu^2$ was calculated. For a typical case the Grashof number was equal to 0.30 ΔT_g which for the largest ΔT_g (pure conduction) was less than that needed to establish the natural convection. On the basis of these calculations, the maximum value of ΔT_g across the annulus can be calculated using the pure conduction solution. This will be modified slightly by radiation heat transfer in locations where the energy deposition is the highest.

If it is assumed that there is no heat transfer across the hole in the Li_2O cartridge and that heat flow is radially outward, then the ΔT_L across the heat generating Li_2O is given by

$$\Delta T_L = \frac{w_L d_L^2 \left[1 - (d')^2 + 2(d')^2 \ln(d')\right]}{16 k_L} \qquad (21)$$

where $d' = d_h/d_L$

TYPICAL RESULTS OF THE PARAMETRIC STUDY

A few of the more important results of the parametric studies leading to the selection of our reference case (where $T_{B(IN)}$ = 625 K and $T_{B(OUT)}$ = 825 K) will now be described.

Figure 9 illustrates lithium oxide maximum temperature as a function of neutron wall loading for a family of tube diameters. Clearly the smaller tube diameters are superior, and if the higher wall loadings are to be achieved, then tube diameters of about 2 cm or 2.5 cm are to be strongly preferred. We do not know definitively how near to the melting point it is possible to operate the Li_2O but a safe value may be approximately 0.80 or about 1575 K; however, the value of the maximum safe Li_2O temperature is still controversial. Therefore, to be even more conservative, we chose a design at 962 K for a reference tube diameter of 0.02m, t_w = 0.5 mm, t_g = 1.0 mm, and t_s = 2.0 mm.

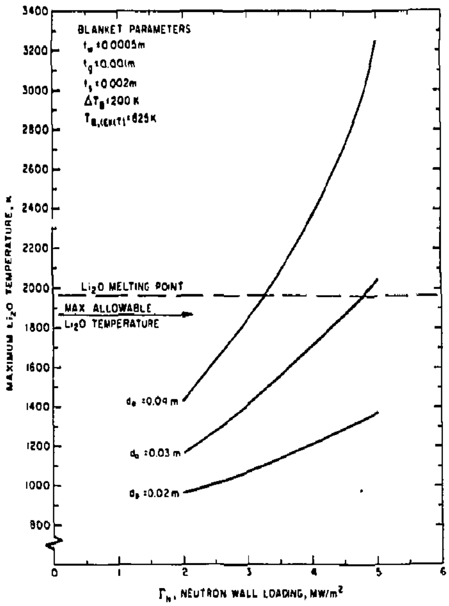

FIG. 9 MAXIMUM Li_2O TEMPERATURE AS A FUNCTION OF WALL LOADING FOR SELECTED TUBE DIAMETERS AT ΔT_B = 200 K

Figure 10 shows maximum tube wall temperatures as a function of wall loading for selected tube diameters. For this parametric study, the wall loading was increased by moving the Canisters closer to the central cell plasma while keeping the total fusion power constant. In addition, the radius of the first wall of the Canisters was kept constant, and the number of Canisters per ring module was reduced appropriately as the Canisters were moved closer to the plasma. The helium inlet and exit bulk temperatures were also held fixed at 625 K and 825 K, respectively.

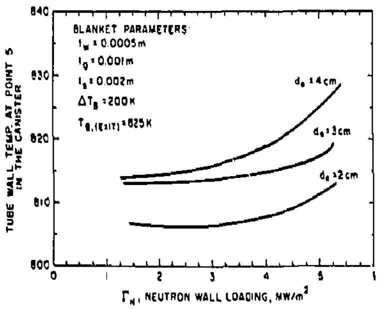

FIG. 10 MAXIMUM TUBE WALL TEMPERATURE AS A FUNCTION OF WALL LOADING FOR SELECTED TUBE DIAMETERS

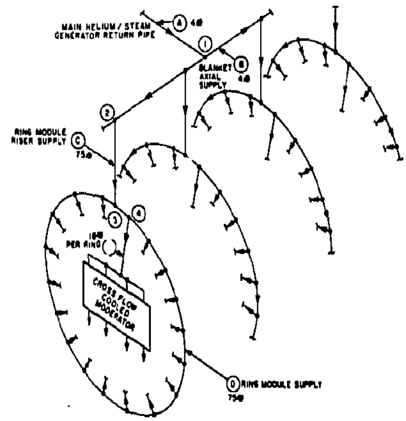

FIG. 11 SCHEMATIC OF COOLANT SUPPLY LINES TO THE INDIVIDUAL CANISTERS OF EACH BLANKET MODULE

The maximum tube-wall temperatures were found to occur close to the exit of the second breeder zone (point 5 on Fig. 7). As can be seen from the results in Fig. 10, this temperature does not vary appreciably for a factor of 2.5 change in the wall loading or a factor of 2 change in the tube diameter. The maximum tube wall temperatures of 807 to 825 K fall within a reasonable range for Tenelon. It should be recalled that the Tenelon tubes only have 1 to 2 atm differential pressure across them, so the stresses are low.

For the reference case where the bulk temperature rise is 200 K, the lithium oxide minimum temperature was estimated to be approximately 666 K, which is above the estimated minimum temperature required to maintain a tritium inventory less than 1 kilogram.

PRESSURE LOSSES AND PUMPING POWER

Calculations were run to estimate the total pressure drop and pumping power for the entire blanket coolant circuit including the primary side of the steam generators. Fig. 11 shows the flows in the ring headers, while Fig. 12 shows the flow path of the helium from the reactor to the steam generators and return. The calculations are discussed in detail in Ref. 1.

The final result for the reference design excluding pipe bend and turning losses was a pressure drop of 27.8 kPa. The pressure losses due to pipe bends and turns in the flow circuit were estimated to be an additional 29.2 kPa. Thus, the total pressure drop is about 57 kPa (∿ 8.3 psi), a modest number that could possibly be reduced further by optimization. In terms of percentage of the blanket thermal power, about 1.3% helium pumping power is required to overcome these flow losses. It should be noted that the blanket/shield part of this flow circuit, i.e., the tube-bank, cross-flow heat exchanger, accounts for less than 25% of the total pressure loss, whereas more than 50% is attributable to losses due to turns, bends, dividing flows and joining flows.

In addition to the thermal-hydraulic analysis, a stress analysis was performed on the tubes and on the Canisters. However, this is beyond the scope of this

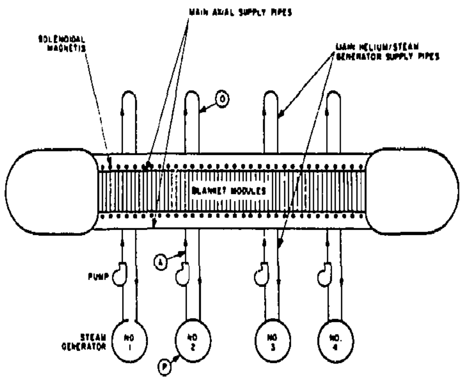

FIG. 12 SCHEMATIC OF COOLANT LOOPS FROM THE BLANKET TO THE STEAM GENERATORS

heat-transfer-oriented paper, and the interested reader is referred to Ref. 1 for details on this and other materials-related topics.

SUMMARY AND CONCLUSIONS

The key characteristics of our reference design are summarized in Table 3. The tube-bank blanket module concept appears to have many potential advantages. These include:

a) The concept of the use of a solid Li_2O breeder material inside of tubes arranged as a two-pass, cross-flow heat exchanger appears to be very attractive.
b) This arrangement separates the tritium from the main helium flow which reduces the tritium recovery problems and makes the isolation of the tritium from the synfuel plant or an electric

TABLE 3 SUMMARY OF THE CANISTER PERFORMANCE DATA

Overall Central-Cell Blanket	
Number of ring modules	75
Number of half Canisters/ring module	36
Number of tubes and rods/half Canister	542
Neutronics	
Volumetric heat generation near the first wall for Γ_N = 2.0 MW/m^2:	
Li_2O cartridges	13.5 MW/m^3
Tenelon tubes	18.0 MW/m^3
Structural : Tubes	
Tube and rod material	Tenelon
Tube outer diameter	0.020 m
Tube wall thickness	0.0005 m
Tube nominal length	2.0 m
Maximum hoop stress	4.0 MPa
Maximum thermal stress	2.7 MPa
Maximum combined stress	6.7 MPa
Tube wall temperature (at exit of TA region where stress is maximum)	758 K
Creep rupture stress of Tenelon at 758 K	250 MPa
Structural: Tritium Breeder Material	
Solid breeder material	Li_2O
Percent theoretical density	90%
Assembled shape	Hollow cylinder
Inner diameter	0.006 m
Outer diameter	0.017 m
Maximum thermal stress (estimated)	∿ 35 MPa
Tensile fracture stress (estimated)	∿ 69 MPa
Maximum temperature at inner surface (at exit of turnaround zone)	962 K
Minimum temperature at inner surface (at inlet to first breeder zone)	666 K
Thermal-Hydraulics of Tube Bank	
Coolant	Helium
Pressure	5 MPa
Inlet temperature	625 K
Outlet temperature	825 K
Minimum gap between tubes	0.002 m
Maximum Reynolds number	∿ 34,000
Maximum flow velocity	∿ 16 m/s
Average heat transfer coefficient	∿ 2000 W/m^2-K
Pressure drop inside Canister	0.016 MPa
Pumping power/half Canister	5.71 kW
Power removed by tube bank coolant/half Canister	1.12 MW
% pumping power in cooling Canister tube bank	0.51%

powerplant very effective.

c) The small purge helium flow inside the tubes for removing tritium from the Li_2O need only be at one or two atmospheres lower pressure than the main helium coolant flow to ensure that almost no tritium will get into the main flow in the event of a leak. This allows the hot tubes to be thin and still operate at very low stress levels, since they are almost pressure balanced.

d) The closely-spaced, cross-flow tube bank arrangement results in almost uniform tube wall temperatures around the circumference and high heat transfer coefficients; this helps to avoid hot spots on the tube walls.

e) The maximum tube wall temperature is only about 810 K at the worst point (near the exit of the second breeder section); it is only about 758 K where the combined stresses are a maximum of 5.6 MPa. These stresses are very low for Tenelon.

f) The maximum and minim·ı Li_2O temperatures are 962 K and 666 K, respectively. This range of temperatures should result in good tritium release from the Li_2O and low tritium inventories.

g) The fractional pressure drop across the tube bank is only 0.32%, which results in a ratio of the pumping power required to the thermal power removed of only 0.51%.

h) A great deal of refinement and optimization of the tube bank design is possible, since some tailoring of the tube diameters and spacings can be used to compensate for the near-exponential decrease in the internal heat generation.

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