DESIGN WINDOW CALCULATIONS
FOR A CONSTANT Q' LITHIUM BLANKET
COMPARING LITHIUM AND SODIUM COOLANTS

P.Gierszewski
B.Mikic
N.Todreas

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FUSION TECHNOLOGY PROGRAM

Massachusetts Institute of Technology
Cambridge, MA 02139

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ABSTRACT

In previous work[1,2], a design window approach has been applied to a liquid metal cooled, stagnant lithium breeding blanket, where the cooling tubes are spaced such that they all have the same heat flux per unit length (constant q'). This report is partly supplemental in that it is a detailed clarification of the equations and assumptions used, including several refinements. However, it also includes documentation for a revised version of the WINDOW code used to generate the design windows, and (as an example of the usefulness of the design window approach) a comparison of lithium cooling to sodium cooling of this blanket. The results confirm the desirability of lithium as a coolant.

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Nomenclature

a_i - radial half-width of region cooled by i^{th} cooling tube (m)

b_i - azimuthal half-width of region cooled by i^{th} cooling tube (m)

B - magnetic field strength (T)

c - defined by Eqn. (10)

C_p - specific heat of coolant (J/kg-^oC)

C_1 - pumping power ration

D_h, D_t - header and cooling tube diameter (m)

f - defined by Eqns. (23) and (24)

F_c - allowance factor in pressure loss calculations

h - heat transfer coefficient (W/m^2-^oC)

k_c, k_{Li}, k_s thermal conductivity of coolant, structure and lithium pool (W/m-^oC)

L - major on-axis circumference of reactor (m)

M - blanket energy multiplication factor

n - number of coolant tubes per header

N - number of blanket modules (or headers) azimuthally

N_t - total number of coolant tubes

Nu - Nusselt number

$\Delta P_h, \Delta P_t$ - header and total pressure loss (Pa)

q' - heat load per unit length (W/m)

q''_w - first wall neutron energy loading (W/m^2)

$q'''(r)$ - volumetric heat generation rate in blanket (W/m^3)

Q - total power removed per blanket module (W)

Q_{total} - total power removed from all modules (W)

r - radial distance from first wall (m)

R_i - radial position of i^{th} coolant tube (m)

R_w - first wall radius (m)

R_{wo} - reference first wall radius for neutronics calculations (m)

S - coefficient in $q'''(r)$ (1/m)

S_i - fitted reference coefficient from neutronics calculations (m)

t_h, t_t - header tube and coolant tube thickness (m)

T_{in} - inlet temperature (^oC)

T_{max} - maximum lithium pool temperature (^oC)

ΔT_c - coolant temperature rise across blanket (^oC)

ΔT_f - film temperature drop (^oC)

ΔT_m - temperature drop between coolant tube and maximum in pool (^oC)

ΔT_w - wall temperature drop (^oC)

u_h - coolant velocity at inlet (m/s)

v - fitted coefficient in $q'''(r)$ (1/m)

x - axial length of coolant tubes (m)

z - radial thickness of blanket (m)

α_c, α_s - fraction of blanket volume occupied by coolant and structural material (exclusive of header region)

μ - coolant viscosity (kg/m-s)

ρ - coolant density (kg/m^3)

σ_c, σ_s - electrical conductivity of coolant and structure (1/Ω-m)

σ_h - hoop stress (Pa)

σ_y - structural material design yield stress limit (Pa)

Design Window Calculations for a Constant q' Lithium Blanket Comparing Lithium and Sodium Coolants

1. Introduction

An interesting fusion reactor coolant/breeding material combination is liquid metal cooling with a stagnant lithium pool breeding region. A design methodology is developed to identify the constraints on a constant q' blanket model (Figure 1). Here, coolant tubes (running parallel to the main toroidal field to minimize MHD pressure loss) are distributed to match the volumetric heating rate. Each tube receives the same heat input. This design emphasizes fewer tubes and lower thermal stresses.

The design window approach is to take basic thermal-hydraulic, structural and neutronic constraints, and use them to define limit lines in design parameter space. Here the length of the coolant tubes (x) and the number of tubes per module header (n) are used as the unspecified parameters that must be chosen consistent with the constraints and design objectives.

The limiting constraints in this blanket model are:

- maximum lithium pool temperature (vapor pressure becomes too large);
- maximum coolant temperature (limited by corrosion of tube material);
- minimum coolant temperature (coolant must be liquid, and hot enough for useful energy generation efficiency);
- maximum stress (primary membrane stresses must be less than the structural material yield strength);
- maximum neutron fluence (limited by materials damage);
- minimum tritium breeding ratio (reactor must be self-sustaining);

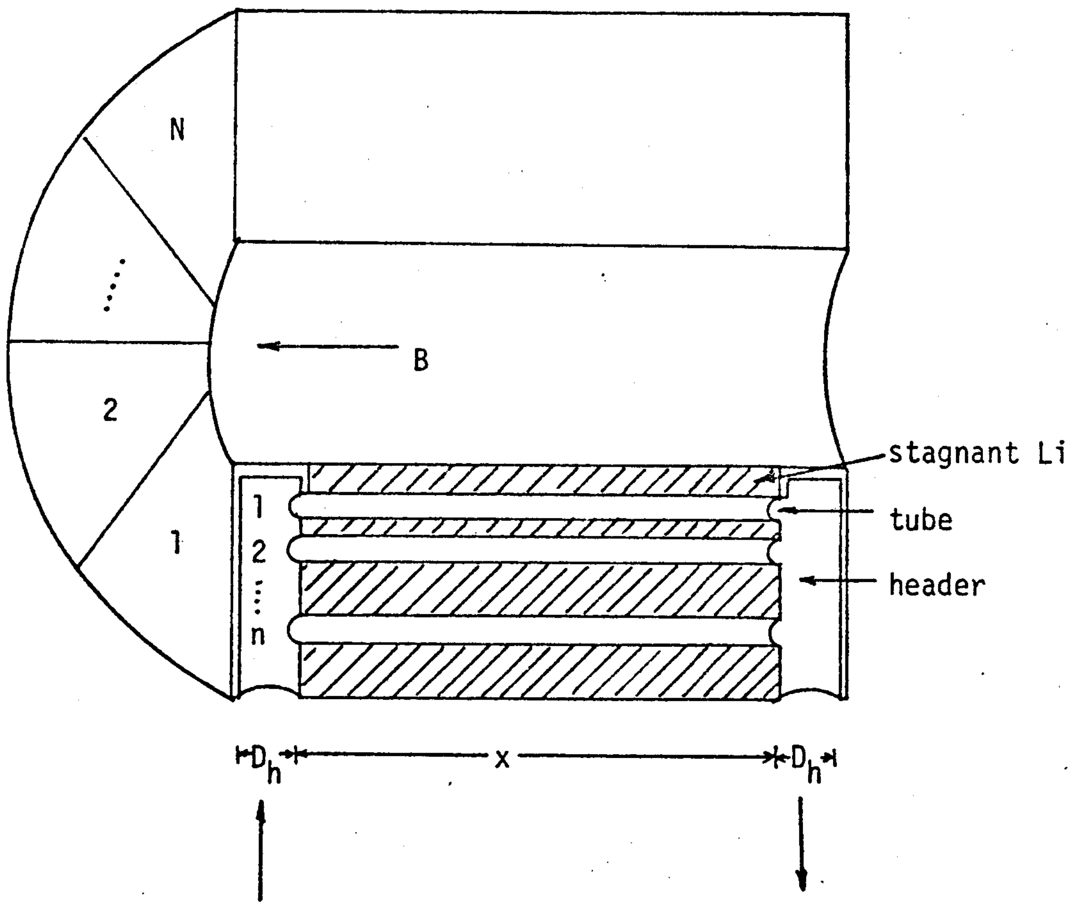

Figure 1. Constant q' Blanket Model

- maximum number of cooling tubes (reliability decreases with complexity);
- maximum pumping power to heat removal ratio (economic limit);
- maximum header diameter (limited by space).

There is sufficient information available to choose values for most of these constraints, irrespective of reactor parameters. For example, the maximum lithium pool temperature is about 900°C. This allows a margin of safety from the boiling point (1300°C), and keeps the vapor pressure low (less than 13 kPa) such that the blanket module need not be pressurized. The maximum pool temperature and other such constraints are implicitly included in the design window calculations.

The remaining constraints, notably the maximum neutron fluence, the maximum number of coolant tubes and the maximum header diameter, are more susceptible to other design considerations not included here. Accordingly, these constraints are drawn as contours or limit lines, $n = n(x)$, in the n-x design parameter space, and bound the acceptable design window.

2. Design Window Analysis

In this analysis of the constant q' blanket, materials properties are assumed known and temperature independent, some typical or reference reactor parameters are used, and values of the constraints are taken as given. In addition, a fitted function is used to describe the volumetric heating rate through the blanket. The intent is to derive expressions for $n = n(x)$ based explicitly on the total number of coolant tubes (N_t), the header diameter (D_h) and the first wall neutron loading (q_w'').

The first limit line $n = n(x)$ follows easily from the expression for the total number of coolant tubes,

$$N_t = NnL/x \tag{1}$$

where N is the number of blanket modules (azimuthally), and L is the major circumference on axis.

The remaining equations require considerably more work. From neutronics calculations, the volumetric heating rate $q'''(r)$ is expressed approximately as

$$q'''(r) = Sq''_w e^{-vr} \tag{2}$$

where S and v are fitted coefficients, and r is the distance from the first wall. Since the calculations are nominally for some reference first wall radius R_{wo}, Eqn. (2) must be generalized to handle other R_w. Now for the same wall loading and total blanket volume

$$q''' = q''_w . 2\pi R_w L/\text{volume} \tag{3}$$

while for the same wall loading and blanket thickness

$$q''' = q''_w \; 2\pi R_w L/\{\pi(R_w+z)^2 - \pi R_w^2\}L \tag{4}$$

In either case, q''' increases as R_w increases, so

$$q'''(r) \simeq \frac{R_w}{R_{wo}} \; S_o q''_w e^{-vr} \tag{5}$$

which strictly is only correct for constant blanket volume. Note also that while $q'''(r)$ may be correct for any fraction of lithium coolant in the blanket, the fitted coefficients will not be correct over a wide range of coolant volume fraction for other liquid metals.

Given this heat generation rate, determine the size and location of the coolant tubes. Consider an arbitrary value of n. The tubes must be radially spaced such that the constant q' condition is met. Since q''' decreases with r, the tubes are spaced further apart at the outer blanket edge than near the plasma. In fact, the radial distance between tubes is given by[1]

$$2a_i = 2a_1 \frac{R_w+R_1}{R_w+R_i} e^{v(R_i-R_1)} \tag{6}$$

where $2a_i$ is the radial width of the blanket volume "covered" by the cooling tube at radius R_i from the first wall. It is in the region around the outer tubes that the maximum blanket temperature occurs, and here

$$a_n = \frac{D_t}{2} \frac{R_w}{R_n+R_w} e^{-vD_t/2} e^{vR_n} \tag{7}$$

which assumes D_t (tube diameter) << $2R_w$ and, more significantly, that $a_i = R_1 \approx D_t/2$. This latter implies that the tubes are very closely spaced (radially) near the first wall.

Now $a_n = z - R_n$, where z is the blanket thickness. So by determining D_t from other considerations, Eqn. (7) can be solved for R_n. Ideally, D_t comes from the following system of equations:

$$z = \sum_{i=1}^{n} 2a_i \tag{8a}$$

$$2a_i \approx D_t \frac{R_w}{R_w+R_i} e^{-vD_t/2} e^{vR_i} \tag{8b}$$

$$R_i = \sum_{j=1}^{i} 2a_j - a_i \tag{8c}$$

However, this is a complex problem. But D_t is only needed in the calculation of the maximum pool temperature, and there it is not a dominant factor. Accordingly, use an approximation (accurate for large n) to get reasonable results. Rearrange $z = \Sigma\, 2a_i = \Sigma\, 2a(R_i)$ to obtain,

$$n = \frac{z}{2a(R)} \simeq \int_0^z \frac{dR}{2a(R)} \tag{9}$$

Therefore, using Eqn. (6),

$$n \simeq \frac{e^{vDt/2}}{D_t v} \{1-e^{-vz} + \frac{1-(1+vz)e^{-vz}}{R_w v}\} = \frac{e^{vDt/2}}{D_t} \frac{c}{v} \tag{10}$$

where c is the expression in brackets.

Now D_t is expected to be small, so Eqn. (10) can be reduced to give $D_t \sim c/nv$. But for a little more accuracy, expand the exponential, $D_t(1 - vD_t/2) \sim c/nv$. Solving the quadratic in D_t and taking the correct root

$$D_t \simeq (1-\sqrt{1-2c/n})/v \tag{11}$$

Using this value of D_t, Eqn. (7) can be solved for R_n, which is needed in calculating the maximum lithium pool temperature, T_{max}.

In particular, the maximum temperature difference between the lithium pool and the coolant is given by[1,2]

$$\Delta T_m = \frac{q'''(R_n)}{2k_{Li}} \left[(b_n - \frac{\pi}{4} a_n)^2 + \frac{1}{2} (a_n^2 - \frac{D_t^2}{4}) + 4\frac{a_n b_n}{\pi} \ln \frac{2a_n}{D_t} \right] \tag{12}$$

where $a_n = \frac{D_t}{2} \cdot \frac{R_w}{R_w+R_n} \quad e^{-vD_t/2} \; e^{vR_n}$

$b_n = \pi(R_w+R_n)/N$

(this assumes $b_n > a_n$ - otherwise simply interchange their definitions).

This can be written as

$$\Delta T_m = q_w'' f \tag{13}$$

where f is a function of known quantities.

The maximum blanket temperature is T_{max}, where

$$T_{max} = T_{in} + \Delta T_c + \Delta T_f + \Delta T_w + \Delta T_m \tag{14}$$

For given T_{in} and ΔT_c (coolant temperature rise), and ΔT_m from Eqn. (13), only the film (ΔT_f) and wall (ΔT_w) temperature drop need be found. The wall temperature drop is easily obtained as

$$\Delta T_w = \frac{Nu\ k_c}{2\ k_s} \ln(1+ \frac{2t_t}{D_t})\ \Delta T_f \tag{15}$$

where t_t and ΔT_f are still undetermined. (Under the blanket conditions, Nu is approximately constant over a wide range of flow velocities.)

The total power absorbed (and extracted) from each blanket module can be expressed in terms of the coolant temperature rise,

$$Q = u_h \frac{\pi D_h^2}{4} \rho c_p \Delta T_c \tag{16}$$

or in terms of the heat transfer rate to the coolant,

$$Q = n\ h\Delta T_f\ x\pi D_t = n\ Nu\ k_c \Delta T_f\ x\pi \tag{17}$$

or in terms of the pumping power to heat removal ratio C_1,

$$Q = \Delta P_t \, \rho u_h \, \frac{\pi D_h^2}{4} \, / \, c_1 \tag{18}$$

or in terms of the absorbed energy flux

$$Q = \int_0^z q'''(r) \times \frac{2\pi}{N} (R_w + r) \, dr \tag{19}$$

Here U_h is the coolant velocity in the headers, and ΔP_t is the total pressure drop. Using Eqn. (5), Eqn. (19) becomes

$$NQ = q_w'' \, 2\pi R_w x M \tag{20}$$

$$M = \frac{S_o}{R_{wo} v^2} \{1 + R_w v - (1 + vz + R_w v) e^{-vz}\} \tag{21}$$

where M is the effective blanket energy multiplication factor since $q_w'' \, 2\pi R_w x$ is the incident neutron power. (It is assumed that the first wall thermal load is removed by a separate cooling system.)

Returning to the film temperature drop, combine Eqns. (17) and (20) to obtain

$$\Delta T_f = q_w'' \, 2R_w M \, / \, Nn \; Nu \; k_c \tag{22}$$

Since T_{max} is a known constant, Eqns. (13), (14), (15) and (22) can be rearranged to yield

$$q_w'' = \frac{T_{max} - T_{in} - \Delta T_c}{\frac{2R_w M}{nN \; Nu \; k_c}\left[1 + \frac{Nu \; k_c}{2 \; k_s} \; \ln\left(1 + \frac{2t_t}{D_t}\right)\right] + f} \tag{23}$$

The ratio t_t/D_t comes from the hoop stress limit, which is (because liquid metal coolants operate at low pressure)

$$\frac{D_t}{2t_t} \Delta P_t = \sigma_h \leq \sigma_y \tag{24}$$

and from combining Eqns. (16) and (18) to give

$$\Delta P_t = C_1 \rho c_p \Delta T_c \tag{25}$$

So Eqn. (23) gives the second limit line in terms of the wall loading. It is independent of x because the temperature constraints can be met for arbitrary x by suitable flow rates.

This brings up the final limit line which, by using a maximum hoop stress and a header diameter limit, restricts the maximum possible flow rate. In particular, it relates the maximum flow velocity to the maximum pumping power ratio through the pressure drop.

A general expression for the total pressure drop would include (1) MHD pressure loss in the header where flow is perpendicular to the B field, (2) friction pressure loss, (3) MHD pressure loss at corners, and (4) MHD losses through regions of changing B field. Simple satisfactory solutions are available for the first two terms, but not for the rest. Fortunately, usually only the first term is significant. For the purposes of this analysis, total pressure drop is taken as the MHD pressure loss in the header region multiplied by an allowance factor, F_c:

$$\Delta P_t = F_c \, \Delta P_h \tag{26}$$

This factor is intended to encompass all other pressure loss terms and can be improved as better models become available. From calculations for several typical cases, $F_c = 1.6$ was found to be conservative.[1]

An approximate expression[4] for the header pressure drop, valid for large Hartmann number flow ($H=B(D_t/2)\sqrt{\sigma_c/\mu}$) is

$$\Delta P_h \simeq \frac{H^2 \frac{4}{\pi} \frac{2t_h \sigma_c}{D_h \sigma_s}}{1+\frac{2t_h\sigma_c}{D_h\sigma_s}} \frac{\mu \bar{u}_h}{(D_h/2)^2} z_{total} \tag{27}$$

where $\bar{U}_h$ is the average header velocity and z_{total} is the total header length (blanket plus shield). The blanket inlet header velocity U_h is of particular interest since it determines the total coolant mass flow, and here it is assumed that $U_h \sim \bar{U}_h$, which is correct if the header is tapered towards the first wall. It is also assumed that the blanket and shield are of comparable thickness so that $z_{total} \sim 2z$.

For the same maximum hoop stress in headers and coolant tubes, and allowing the pressure--and hoop stress-- to be equal everywhere if a tube becomes blocked, then

$$D_h/t_h = D_t/t_t \tag{28}$$

Equations (24) to (28) can be rearranged to yield the maximum header velocity consistent with $\sigma_h \leq \sigma_y$:

$$u_{h,max} = \frac{(\pi/8)}{2z\ F_c\ B^2} \left[\frac{C_1\rho c_p \Delta T_c}{\sigma_c} + \frac{\sigma_y}{\sigma_s}\right] \tag{29}$$

where allowance has been made for pressure drop in the two headers.

At this maximum velocity, a restriction on the header diameter would give a maximum flow rate $\rho U_{h,max} \cdot \frac{\pi}{4} D_h^2$. If the header is straight, then the maximum D_h is

$$D_h \leq 2\pi R_W/N \tag{30}$$

but if it tapers in towards the first wall,

$$D_h \leq 2\pi(R_W+z)/N \tag{31}$$

where the diameter of the headers is restricted at the entrance to the blanket module.

The maximum amount of energy that can be removed is then given by Eqn. (16). Combining this with Eqns. (20) and (23) then the third limit line is

$$n = \frac{2R_W MQ\left[1+\dfrac{Nu\ k_c}{2\ k_s}\ln(1+\dfrac{2t_t}{D_t})\right]}{Nu\ k_c\ \{2\pi R_W Mx\ (T_{max}-T_{in}-\Delta T_c) - \bar{f}NQ\}} \tag{32}$$

where $Q = U_{h,max} \cdot \frac{\pi}{4} D_h^2 \cdot \rho c_p\ \Delta T_c$.

So Eqns. (1), (23) and (32) are of the form $n = n(x)$ and describe the limit lines for the design window. These equations are incorporated into a program WINDOW (described in the next section) and are applied to lithium and sodium coolants in the final section.

3. Program WINDOW

The design window analysis has been implemented in the computer program WINDOW. In particular, WINDOW solves the limit line $n = n(x)$ from Eqn. (32), and in the process yields values for the other two limit lines given by Eqns. (1) and (23). It also calculates and prints other interesting design variables such as ΔT_f.

The program is a short FORTRAN program, with the input specifically put on cards in the deck itself. The data needed includes materials data, reactor parameters, limiting parameters and fitted coefficients for q"'(r). These are listed (along with typical values) in the next section. A source listing of the program is enclosed, which indicates exactly how the data if formatted.

The output consists of a list of reactor parameters evaluated at the limit line from Eqn. (32) -- the D_h limit line -- at a range of values of n. Plotting n versus x gives this limit line. Since $q''_w = q''_w(n)$ only, and since $q''_w(n)$ values are output, then the second set of limit lines can also be drawn. The final set is obtained easily from Eqn. (1) -- the N_t limit line. A typical output is enclosed.

The input variables are explained in the program. The output variables are:

- N - number of coolant tubes per blanket module (or header);
- UH - header inlet velocity;
- DELTAP - total pressure drop through blanket;
- DT - coolant tube diameter;
- TT - coolant tube thickness;
- RN - distance of last coolant tube from first wall;
- TM - temperature difference between last coolant tube and maximum temperature in lithium pool;
- TF - film temperature drop at last coolant tube's exit;
- TW - wall temperature drop at last coolant tube's exit;
- QW - first wall neutron loading;
- QTOT - total reactor thermal power;
- X - length of blanket module (without headers);
- ALPHAS - percentage of structure in blanket volume, assuming straight headers;
- ALPHAC - percentage of coolant in blanket volume, assuming straight header
- NT - total number of coolant tubes in reactor.

4. Comparison of Lithium and Sodium Cooling

Liquid metals such as lithium and sodium are good, low pressure, high temperature, radiation damage resistant blanket coolants. Lithium is of special interest because it also moderates neutrons and breeds tritium, has low induced activity, and is quite compatible with the refractory metals. There is still interest, however, in liquid sodium as a near-term reactor coolant, especially in fusion-fission hybrids[5,6]. This is because there is more experience with sodium (i.e., the LMFBR program), it is less corrosive to Fe and Ni based alloys (and stainless steel is the most likely near-term structural material), it is cheaper than lithium, it is inert to tritium, and it is somewhat less reactive[3].

This section compares the two liquid metals as heat transfer agents. The purpose is to further quantify the relative merits of these coolants and to illustrate the design window methodology just developed.

Table 1 lists the parameters examined in this report, and compares them with representative values from some roughly comparable detailed reactor studies. Table 2 lists the materials properties used. While changing these parameters (e.g. TZM rather than stainless steel structure, or N = 20 rather than 100) will quantitatively change the conclusions, it is not believed that this will substantially affect the qualitative conclusions regarding lithium versus sodium coolant.

The volumetric heat generation rate is taken as[1]:

$$q'''(r) = 4.67 \left(\frac{R_w}{3.0}\right) q_w'' \, e^{-4.256r} \quad (r, R_w \text{ in m}) \tag{33}$$

This is strictly only true for lithium pool/lithium coolant, but is assumed

Table 1: Reference Reactor Parameters

Parameter	Examples*			
	Princeton tokamak (7)	UWMAK-III tokamak (8)	ORNL cassette blanket (9)	This analysis
Coolant	He	Li	He	Li/Na
Structural material	Pe-16	TZM	316SS	steel
Breeding pool material	flibe	Li	Li	Li
Magnetic field strength, B(T)	4-16	2-9	---	5
Major circumference, L(m)	69	51	38	60
First wall radius, R_W(m)	3.6	3-5	1.5	3.0
Blanket thickness, Z(m)	0.80	0.60	0.42	1.0
Inlet temperature, T_{in}(^oC)	360	630	77	200/300
Coolant temperature rise, ΔT_c(^oC)	280	350	400	200/300
First wall neutron load, q_w'' (MW/m^2)	1.8	2.5	3.0	≥ 1.0
Pumping power ratio, C_1 (%)	1.6	0.06	1.0	1.0
Number of blanket modules azimuthally, N^*	23	72	15	100
Number of coolant channels, N_t^*	15000	5200	14000	≲ 10000
Header diameter, D_h(m)*	0.11	0.20	0.10	≤ 0.25
Maximum pool temperature, T_{max} (^oC)	850	900	400	600/900

*Since none of the blankets directly compared with the constant q' model of this analysis, some freedom was taken in interpreting parameters and representative values - especially those parameters marked with a star.

Table 2: Materials Properties (10 11 12 13)

Parameter	Lithium 300°C/500°C	Sodium 300°C/500°C
Specific heat, c_p (J/kg-°C)	4290/4180	1300/1260
Electrical conductivity, σ_c (1/Ω-m)	$3.3\times10^6/2.8\times10^6$	$5.7\times10^6/3.7\times10^6$
Thermal conductivity, k_c (W/m-°C)	46./50.	76./67.
Density, ρ (kg/m^3)	505/484	880/856
Melting point at 0.1 MPa	180.	98.
Boiling point at 0.1 MPa	1317.	883.

Thermal conductivity of lithium at 800°C, k_{Li} (W/m-°C) 55.
Thermal conductivity of stainless steel at 500°C, k_s (W/m-°C) 18.5
Electrical conductivity of stainless steel at 500°C, σ_c (1/Ω-m) 9.5×10^5
Stainless steel design yield strength, σ_y (MPa) 60.

reasonable for small volume fractions of sodium coolant (in the examples shown here, there is typically about 6% coolant, 0.6% structure). Furthermore, since the pure lithium case had a breeding ratio of about 1.4,[1] the small amount of sodium coolant should not reduce the breeding unacceptably low.

Figures 1, 2 and 3 show the design windows for lithium and sodium coolant. Figure 1 uses identical reactor parameters (notably $T_{in} = \Delta T_c = 200^oC$, $T_{max} = 900^oC$). The shaded area is the acceptable design window for $N_t < 10000$, $D_h < 0.251$ m and $q_w'' > 1.0$ MW/m^2. Figure 2b takes advantage of the possible higher operating temperature of sodium /steel as compared with lithium/steel). Only the D_h limit line is appreciably changed, and two cases of $T_{in} = 200^oC$, $\Delta T_c = 300^oC$ and $T_{in} = 300^oC$, $\Delta T_c = 200^oC$ are shown. Figure 2a is identical with Figure 1a and is repeated to simplify comparison of the lithium and sodium curves. Figure 3 again uses identical reactor parameters, but T_{max} is dropped to 600^oC and N_t reduced to 5000, to represent near-term reactor objectives. Table 3 compares the blanket parameters at point A--the maximum first wall loading design consistent with the constraints (note, though, that n is an integer, so some leeway was taken with the N_t line).

From all results, it is quite clear that lithium is a better coolant than sodium. Not only does it lead to larger option spaces, but it allows higher wall loading operation, higher total thermal power, and even fewer tubes for operating at a given wall loading. The higher possible temperature of the sodium/steel system allows the optimum sodium design to approach the optimum cooler lithium/steel system (Case 3 compared with Case 1) but is

Figure 1. Design windows for lithium and sodium coolants. $T_{in}=200^{o}C$ $\Delta T_c=200^{o}C$ $T_{max}=900^{o}C$ $N_t < 10000$ $q''_w > 1.0\ MW/m^2$ $D_h < 25.1$ cm.

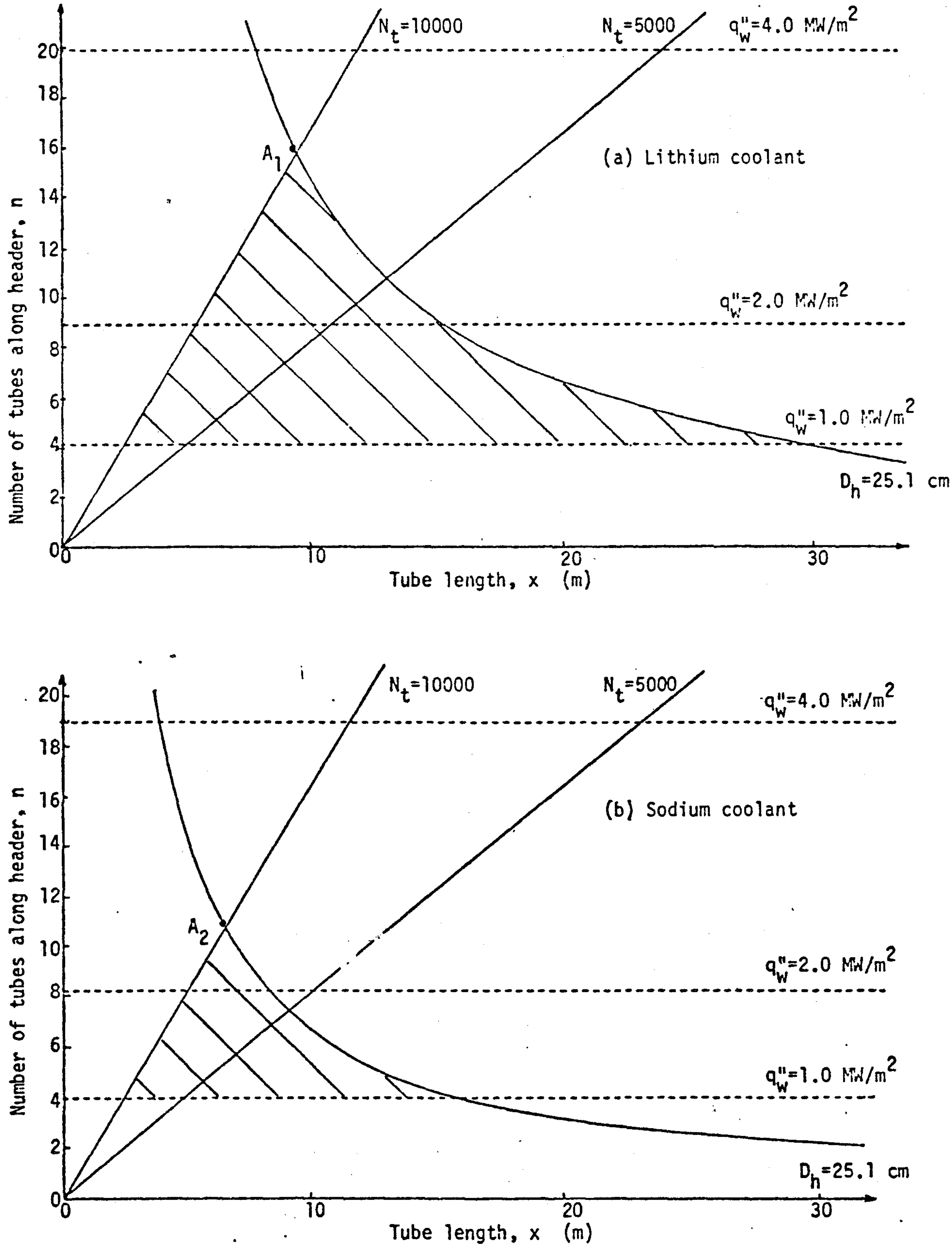

Figure 2. Design windows for lithium and sodium, where the sodium coolant is allowed to be 100 C higher at exit than the lithium coolant.

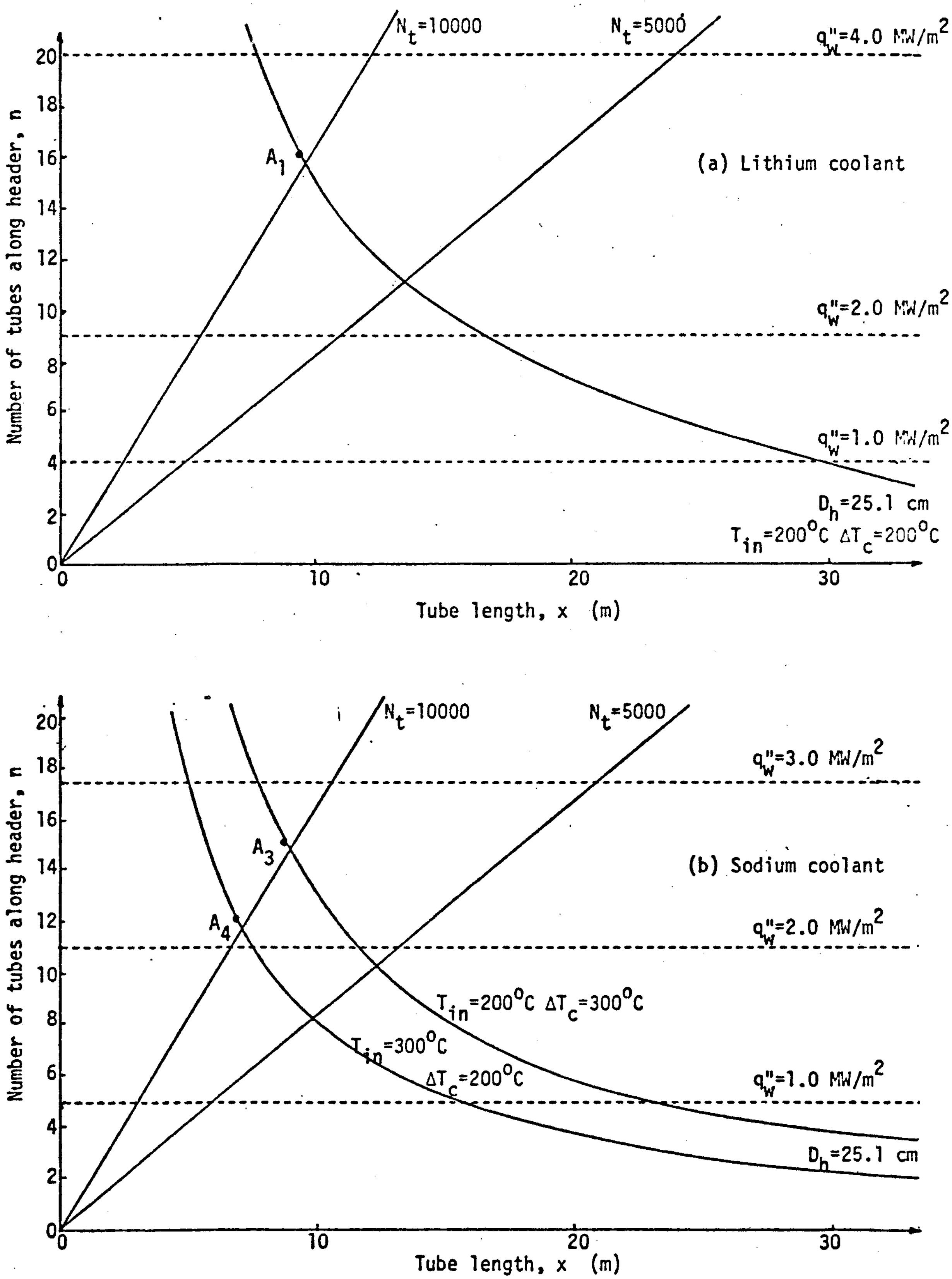

Figure 3. Design windows for lithium and sodium. T_{in}=200°C, ΔT_c=200°C, T_{max}=600°C

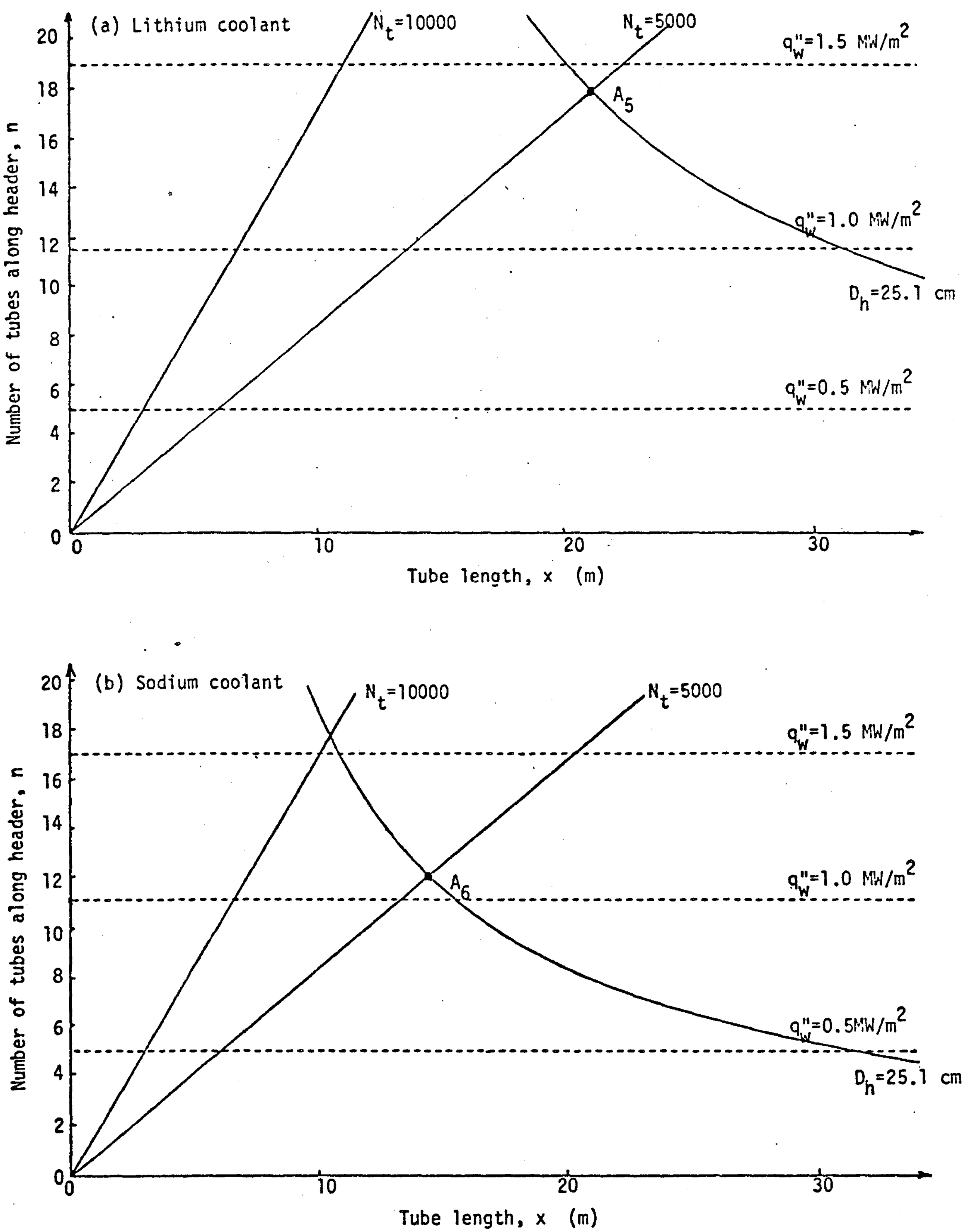

Table 3: Comparison of Lithium and Sodium Coolants for Maximum q''_w Design

Parameter	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Figure	1a	1b	2b	2b	3a	3b
Coolant	Li	Na	Na	Na	Li	Na
T_{in} (^oC)	200	200	200	300	200	200
ΔT_c (^oC)	200	200	300	200	200	200
T_{max} (^oC)	900	900	900	900	600	600
N_t	10300	10500	10300	10500	5100	5000
q''_w (MW/m^2)	3.3	2.6	2.6	2.2	1.4	1.1
Q_{total} (MW)	678	353	503	334	678	353
n	16	11	15	12	18	12
x(m)	9.4	6.3	8.8	7.0	21.	15.
u_h(m/s)	0.32	0.31	0.31	0.31	0.32	0.31
ΔP_t (MPa)	4.3	2.3	3.2	2.2	4.3	2.3
D_t(cm)	1.6	2.4	1.7	2.2	1.6	2.2
t_t(cm)	0.058	0.045	0.046	0.040	0.058	0.042
ΔT_m (^oC)	427	452	356	360	171	181
ΔT_f (^oC)	45.	31.	26.	28.	18.	12.
ΔT_w (^oC)	27.	16.	17.	12.	11.	6.6
α_s(%)	0.86	0.66	0.69	0.58	0.48	0.38
α_c(%)	6.0	8.7	6.4	8.0	3.3	4.9

still not superior. So while sodium is still a viable coolant--all constraints considered here can be met--these results show that lithium coolant is definitely the thermal-hydraulic choice.

These results confirm the conclusion that could be drawn directly from the materials properties (Table 2) themselves. For liquid metal coolants in magnetic fields, two rough figures of merit are ρc_p and σ. The first is a measure of the coolant's ability to absorb heat, and the second is a measure of the resistance to flow in a magnetic field. Ideally, the first should be large and the second small. At 300°C, $(\rho c_p)_{Li} = 2.2\times10^6$ J/m³-°C, $(\rho c_p)_{Na} = 1.1\times10^6$ J/m³-°C, and $\sigma_{Li} = 3.3\times10^6\ (\Omega\text{-m})^{-1}$, $\sigma_{Na} = 5.7\times10^6\ (\Omega\text{-m})^{-1}$. Clearly lithium is superior in both respects. The results of this design window analysis illustrate exactly how these material advantages affect the blanket design.

5. Conclusions

The analysis in this report clarifies and refines the analysis of a liquid metal cooled, stagnant lithium breeding blanket with constant q' coolant tube spacing using a general design window methodology. In particular, expressions are obtained relating basic reactor parameters to constraint curves in n-x space, for the particular constraints of maximum number of coolant tubes (reliability limit), first wall neutron load (design objective) and header diameter (physical geometry limit). A computer program, WINDOW, to calculate the design window curves is documented.

This analysis is then applied to a general comparison of lithium and sodium coolants. The results confirm that lithium is a better heat transfer agent (3.3 MW/m^2 maximum first wall loading as compared with 2.6 MW/m^2, for the best cases considered here), although sodium is still shown to meet the basic constraints considered here. This application also serves to illustrate the usefulness of the design window approach.

6. References

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Appendix A

Source listing of program WINDOW

```
      CCCCC-------------------------------------------------------------------CCCCC
      CCCCC                       PROGRAM WINDOW                              CCCCC
      CCCCC     *WINDOW* GIVES DESIGN WINDOWS IN N2-X SPACE FOR A CONSTANT Q'  CCCCC
      CCCCC  LIQUID METAL COOLED FUSION BLANKET ELECTRICALLY INSULATED FROM A  CCCCC
      CCCCC  STAGNANT TRITIUM BREEDING LITHIUM POOL.  BESIDES MATERIALS       CCCCC
      CCCCC  PROPERTIES, IMAX, TIN, TC, N, Q''', DH, CI, AND BLANKET SIZE ARE  CCCCC
      CCCCC  FIXED.  *WINDOW* WAS WRITTEN BY JIATSCNG CHAO (1978) AND MODIFIED CCCCC
      CCCCC  BY PAUL GIERSZEWSKI (1979) AT M.I.T.                             CCCCC
      CCCCC     J.CHAO, THERMAL-HYDRAULIC AND NEUTRONIC CONSIDERATIONS FOR     CCCCC
      CCCCC  DESIGNING A LITHIUM COOLED TOKAMAK BLANKET, PH.D. THESIS, M.I.T., CCCCC
      CCCCC  DECEMBER, 1978.                                                  CCCCC
      CCCCC-------------------------------------------------------------------CCCCC
0001        REAL KC,KS,KLI,M,L,N2,NU
0002    100 FORMAT(' BLANKET DESIGN FOR CONSTANT Q'' MODEL',//,
           1 ' SYSTEM PARAMETERS:',/,8X,'MAJOR CIRCUMFERENCE (M) ',F6.1,/,
           2 10X,'FIRST WALL RADIUS (M):',F8.3,/,10X,'BLANKET THICKNESS (M):',
           3 F8.3,/,9X,' FIELD STRENGTH (TESLA):',F5.1,/,15X,
           4 'ALLOWANCE FACTOR:',F7.2,/,5X,'Q'''''' COEFFICIENTS - ',
           5 'RWO (M):',F6.2,'    SO (1/M):',F6.2,'   V (1/M):',F7.3,/,
           6         4X,'NUMBER OF AZIMUTHAL SECTORS:',I4,//,' HEAT TRANSFER ',
           7 'PARAMETERS:',/,12X,'PUMPING POWER RATIO:',F9.4,/,2X,
           8 'COOLANT INLET TEMPERATURE (C):',F6.1,/,3X,'COOLANT TEMPERATURE',
           9 ' RISE (C):',F7.2,/,4X,'MAX LITHIUM TEMPERATURE (C):',F5.0,/,12X,
           A 'HEADER DIAMETER (M):',F8.3)
0003    105 FORMAT(///,4X,'N',6X,'UH DELTAP',4X,'DT',4X,'TT',5X,'RN',5X,
           1 'TM',5X,'TF',5X,'TW',6X,'GW  QTOT',6X,'X ALPHAS ALPHAC',5X,'NT',
           2 /,8X,'(M/S)  (MPA)  (CM)  (CM)',4X,'(M)',4X,'(C)     (C)     ',
           3 '(C) (MW/M2)  (MW)      (M)',4X,'(%)',4X,'(%)')
0004    110 FORMAT(1X,F4.0,F8.4,-6PF7.2,2PF6.1,F6.3,0PF7.3,3F7.1,-6PF8.2,F6.1,
           1 0PF7.2,2P2F7.2,0PI7)
0005    120 FORMAT(///,' MATERIALS PROPERTIES:',/,1X,'COOLANT HEAT CAPACITY ',
           1 '(J/KG-C):',F7.1,/,1X,6X,'COOLANT DENSITY (KG/M3):',F8.1,/,
           2 10X,'COOLANT NUSSELT NUMBER:',F6.1,/,11X,'YIELD STRENGTH (MPA):',
           3 -6PF8.2,/,' CONDUCTIVITY (1/OHM-M)    COOLANT:',1PE9.1,
           4 '    STRUCTURE:',E9.1,/,1X,'THERMAL CONDUCTIVITY (W/M-C)    ',
           5 'COOLANT:',0PF6.1,'    LITHIUM POOL:',F6.1,'    STRUCTURE:',F6.1)
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      CCCCCCC---------- INPUT VARIABLES ----------------------------  CCCCCCC
      C   B-MAXIMUM MAGNETIC FIELD (TESLA)
      C   CP-SPECIFIC HEAT OF COOLANT (J/KG-C)
      C   CI-PUMPING POWER TO HEAT REMOVAL POWER RATIO
      C   CONDC-COOLANT CONDUCTIVITY (1/OHM-M)
      C   CONDS-ELECTRICAL CONDUCTIVITY OF TUBE STRUCTURAL MATERIAL (1/OHM-M)
      C   DH-HEADER DIAMETER (M)
      C   FC-SAFETY FACTOR IN ESTIMATING MHD PRESSURE DROP
      C   KC-THERMAL CONDUCTIVITY OF COOLANT (W/M-C)
      C   KLI-THERMAL CONDUCTIVITY OF LIQUID LITHIUM (W/M-C)
      C   KS-THERMAL CONDUCTIVITY OF TUBE STRUCTURAL MATERIAL (W/M-C)
      C   L-TOTAL CIRCUMFERENTIAL LENGTH OF BLANKET (M)
      C   N-NUMBER OF AXIMUTHAL COOLING SECTORS
      C   NU-COOLANT NUSSELT NUMBER
      C   N2-NUMBER OF COOLANT TUBES PER HEADER
      C   RHO-COOLANT DENSITY (KG/M3)
      C   RW-INNER BLANKET RADIUS (M)
      C   RWO-REFERENCE FIRST WALL RADIUS (M)
      C   SO-FITTED COEFFICIENT IN Q''' FUNCTION (W/M3)/(W/M2)
      C   SY-MAXIMUM ALLOWABLE HOOP STRESS (N/M2)
      C   TC-CHANGE IN COOLANT TEMPERATURE FROM INLET TO OUTLET (C)
```

```
C     TIN-COOLANT INLET TEMPERATURE (C)
C     TMAX-MAXIMUM TEMPERATURE IN LITHIUM POOL (C)
C     V-FITTED COEFFICIENT IN Q''' FUNCTION (1/M)
C     Z-BLANKET THICKNESS (M)
      B=5.0
      CI=0.01
      CONDC=3.3E6
      CONDS=9.50E5
      CP=4290.
      DH=0.251
      FC=1.6
      KC=46.
      KLI=55.
      KS=18.5
      L=60.
      N=100
      NU=6.9
      N2BGN=3
      N2DLT=2
      N2END=21
      PI=3.14159
      RHO=505.
      RW=3.0
      RWO=3.0
      SO=4.67
      SY=60.E6
      TIN=200.0
      TC=200.
      TMAX=600.
      V=4.256
      Z=1.00
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      WRITE(6,100) L,RW,Z,B,FC,RHO,SO,V,N,CI,TIN,TC,TMAX,DH
      WRITE(6,120) CP,RHO,NU,SY,CONDC,CONDS,KC,KLI,KS
      WRITE(6,105)
      ZTOT=2.0*Z
      DH=PI*(SY/CONDS+CI*RHO*CP*TC/CONDC)/(8.*FC*ZTOT*B*B)
      DELTAP=CI*RHO*CP*TC
      M=((1+RW*V)*(1-EXP(-V*Z))-Z*V*EXP(-V*Z))*SO/(RWO*V*V)
      Q=N*RHO*CH*PI*DH*DH*CP*TC*0.25
      N2=N2BGN
CCCCC----CALCULATE DIAMETER AND THICKNESS OF TUBES ---------------------
      CC=1.-EXP(-V*Z)+(1.-(1.+V*Z)*EXP(-V*Z))/(RW*V)
   20 DT=(1.-SQRT(1.-2*CC/N2))/V
      TT=0.50*DT*DELTAP/SY
      TH=TT*DH/DT
CCCCC---- CALCULATE RADIAL POSITION OF LAST TUBE IN BLANKET -------------
      RN=0.5*Z
      CC1=0.5*DT*RW*EXP(-V*DT/2)
   11 RZ=RN+CC1*EXP(V*RN)/(RW+RN)
      IF(RZ.GE.Z) GO TO 10
      RN=RN*1.001
      GO TO 11
CCCC---- CALCULATE QW AND TEMPERATURES ---------------------------------
   10 BN=PI*(RW+RN)/N
      AN=Z-RN
      IF(BN.GT.AN) GO TO 12
      AN=BN
```

```
      UN=Z-RN
   12 TM=(BN-AN*PI/4.)**2+(AN*AN-DT*DT/4.)/2.+4.*AN*BN*ALOG(2.*AN/DT)/PI
      TM=TM*SO*RW*EXP(-V*RN)/(2.*RWO*KLI)
      Q1=1.+ALOG(1.+2.*TT/DT)*0.50*NU*KC/KS
      QW=(TMAX-TIN-TC)/(2.*M*RW*Q1/(N2*N*NU*KC)+TM)
      TM=TM*QW
      TF=(TMAX-TIN-TC-TM)/Q1
      TW=TMAX-TIN-TC-TM-TF
CCCC----CALCULATE BLANKET SIZE AND NON-LITHIUM FRACTIONS -----------------
      X=RHO*UH*CP*TC/(4.*N2*NU*KC*TF)*DH*DH
      ALPHAS=N*(2*DH*TH*Z+N2*DT*TT*X)/(Z*(2*DH+X)*(2*RW+Z))
      ALPHAC=N*(2*DH*DH*Z+N2*DT*DT*X)/(4*Z*(2*DH+X)*(2*RW+Z))
      NT=N*N2*L/X
      WRITE(6,110)N2,UH,DELTAP,CT,TT,RN,TM,TF,TW,QW,Q,X,ALPHAS,ALPHAC,NT
      N2=N2+N2DLT
      IF(N2.GT.N2END) STOP
      GO TO 20
      END
```

Appendix B

Sample output of program WINDOW

This output is for Case 5 of Table 3.

BLANKET DESIGN FOR CONSTANT Q' MODEL

SYSTEM PARAMETERS:

```
       MAJOR CIRCUMFERENCE (M)    60.0
         FIRST WALL RADIUS (M):    3.000
        BLANKET THICKNESS (M):    1.000
      FIELD STRENGTH (TESLA):    5.0
            ALLOWANCE FACTOR:    1.60
  Q''' COEFFICIENTS - RHO (M):    3.00    SO (1/M):  4.67    V (1/M):  4.256
 NUMBER OF AZIMUTHAL SECTORS: 100
```

HEAT TRANSFER PARAMETERS:

```
          PUMPING POWER RATIO:    0.0100
 COOLANT INLET TEMPERATURE (C): 200.0
  COOLANT TEMPERATURE RISE (C): 200.00
   MAX LITHIUM TEMPERATURE (C): 600.
            HEADER DIAMETER (M):    0.251
```

MATERIALS PROPERTIES:

```
COOLANT HEAT CAPACITY (J/KG-C): 4290.0
     COOLANT DENSITY (KG/M3):    505.0
       COOLANT NUSSELT NUMBER:      6.9
         YIELD STRENGTH (MPA):     60.00
CONDUCTIVITY (1/OHM-M)    COOLANT:  3.3E 06    STRUCTURE:  9.5E 05
THERMAL CONDUCTIVITY (W/M-C)    COOLANT:  46.0   LITHIUM POOL:  55.0    STRUCTURE:  18.5
```

N	UH (M/S)	DELTAP (MPA)	DT (CM)	TT (CM)	RN (M)	TM (C)	TF (C)	TR (C)	QW (MW/M2)	QTOT (MW)	X (M)	ALPHAS (%)	ALPHAC (%)	NT
3.	0.3165	4.33	10.7	0.388	0.579	166.3	21.1	12.6	0.29	678.5	107.66	1.84	12.73	167
5.	0.3165	4.33	5.7	0.204	0.660	166.9	20.7	12.4	0.47	678.5	65.74	0.92	6.34	456
7.	0.3165	4.33	3.9	0.140	0.708	167.7	20.2	12.1	0.64	678.5	48.09	0.67	4.63	873
9.	0.3165	4.33	2.9	0.106	0.741	168.5	19.7	11.8	0.81	678.5	38.32	0.57	3.92	1409
11.	0.3165	4.33	2.4	0.086	0.766	169.3	19.2	11.5	0.96	678.5	32.17	0.52	3.57	2051
13.	0.3165	4.33	2.0	0.072	0.786	169.9	18.8	11.3	1.12	678.5	27.78	0.49	3.41	2808
15.	0.3165	4.33	1.7	0.062	0.802	170.6	18.4	11.0	1.26	678.5	24.68	0.48	3.34	3646
17.	0.3165	4.33	1.5	0.055	0.816	171.2	18.0	10.8	1.40	678.5	22.21	0.48	3.34	4592
19.	0.3165	4.33	1.3	0.049	0.827	171.8	17.6	10.6	1.53	678.5	20.30	0.49	3.37	5616
21.	0.3165	4.33	1.2	0.044	0.837	172.4	17.3	10.3	1.65	678.5	18.73	0.49	3.42	6725