# THERMAL HYDRAULIC ANALYSES OF TWO FUSION REACTOR FIRST WALL/BLANKET CONCEPTS*

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## Summary

A comparative study has been made of the thermal hydraulic performance of two liquid lithium blanket concepts for tokamak-type reactors. In one concept lithium is circulated through 60-cm deep cylindrical modules oriented so that the module axis is parallel to the reactor minor radius. In the other concept helium carrying channels oriented parallel to the first wall are used to cool a 60-cm thick stagnant lithium blanket. Paralleling studies were carried out wherein the thermal and structural properties of the construction materials were based on those projected for either solution-annealed 316-stainless steel or vanadium-base alloys. The effects of limitations on allowable peak structural temperature, material strength, thermal stress, coolant inlet temperature, and pumping power/thermal power ratio were evaluated. Consequences to thermal hydraulic performance resulting from the presence of or absence of a divertor were also investigated. For the case of lithium cooled modules operated in a reactor without a divertor, the following results were obtained: (a) with stainless steel as construction material and a peak structural temperature of 500°C, the neutron wall loading and coolant exit temperature are limited to ≤ 2 MW/m$^2$ and ≤ 480°C, respectively, by thermal stress criteria, and (b) with vanadium as construction material and a peak structural temperature of 650°C, the neutron wall loading and coolant exit temperature are limited to ≤ 8 MW/m$^2$ and ≤ 620°C, respectively, by a combination of constraints involving the peak structural temperature and the minimum coolant exit temperature. For the same cases in a reactor with a divertor, the maximum allowable neutron wall loading increases by from 40% (for vanadium) to 90% (for stainless steel). For the case of a helium cooled stagnant blanket interfaced with a helium cooled stainless steel first wall assembly, the maximum wall loading is limited by thermal stress criteria to ≤ 2.5 MW/m$^2$ without a divertor and to ≤ 5.0 MW/m$^2$ with a divertor.

## Introduction

In order to shed some light on the question of optimum power cycle concepts for commercial fusion plants, a series of studies was carried out to evaluate and compare alternative breeding/heat-transfer/power-conversion systems. As a first step in providing a basis for parametric investigations of energy conversion systems for commercial reactors,[1,2] analyses of first wall/blanket thermal-hydraulic response were performed with the life-limiting properties of the structural materials as the primary constraints. The thermal hydraulic calculations are based on a set of reference design parameters as given in Table 1.

In work completed thus far, two generically similar first wall/blanket concepts have been evaluated. One involves the use of flowing lithium as a heat transfer and breeding medium in a modular blanket cell of the type shown in Fig. 1. The other uses pressurized helium as the heat transfer fluid flowing (in channels) through a "sea" of stagnant liquid lithium as illustrated in Fig. 2. Instead of basing the analyses on arbitrarily selected materials about which little is

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Table 1. Reference Design Parameters for Comparisons of Stainless Steel and Vanadium Alloy Systems

| | |
|---|---|
| Reactor Major Radius | 8.0 m |
| Central Core Radius | 3.0 m |
| First Wall Radius | 3.4 m |
| Radiation and Particle Load Factor | |
| with divertor | 0.10 |
| without divertor | 0.25 |
| Blanket Thickness | 0.6 m |
| Shield Thickness | 0.9 m |
| Magnet Thickness | 0.52 m |
| Basic Design | Modular |

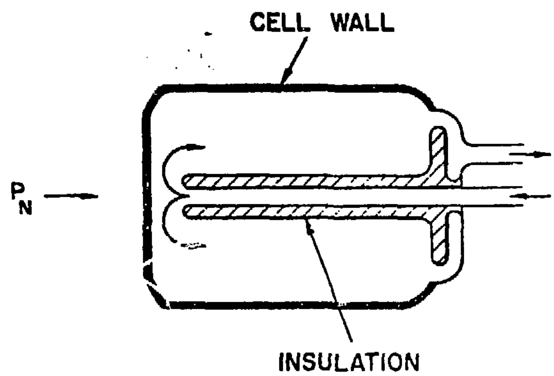



Figure 1. Simplified Model of the Lithium Blanket Cell Used in the Thermal Hydraulic Analyses.

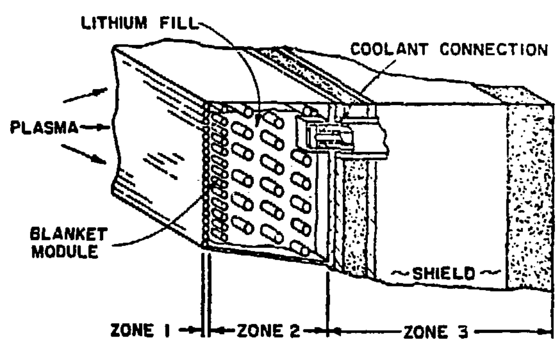



Figure 2. Simplified Model of the Helium Cooled Stagnant Lithium Blanket Used in the Thermal Hydraulic Analyses.

known regarding (a) behavior in the anticipated harsh radiation environment and (b) compatibility with the proposed coolants, solution-annealed Type-316 stainless steel and vanadium-base alloys were selected for initial study as there appeared to be relatively more data available to define life-limiting properties[3] under currently conceived fusion reactor operating conditions.

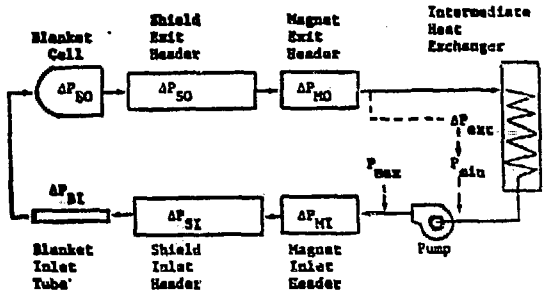
## Development of the Computational Algorithms

Mathematical models that described the thermal hydraulic response of the two blanket concepts illustrated in Figs. 1 and 2 were formulated and programmed into a computer code capable of performing steady-state energy balance calculations. The details of these mathematical models and descriptions of the computer code (BLANKET) have been presented in other reports[2,4] and, hence, will only be summarized briefly herein.

### Flowing Lithium Cooled First Wall/Blanket Concept

The use of an electrically conducting fluid, like lithium, in the presence of large magnetic fields gives rise to a number of adverse fluid dynamic effects of which the most serious is the pressure loss due to magnetohydrodynamic (MHD) interactions. In calculating the total pressure drop for the blanket cell concept in Fig. 1, the coolant flow path was divided into four regions[2,4]: (a) inlet to blanket, (b) return through the blanket cell annulus, (c) inlet and exit through shield, and (d) inlet and exit through magnets. (A schematic representation of the pressure drop terms is shown in Fig. 3.) As the magnetic field is not constant across the blanket, the shield, and the magnet, the magnet field strength, B, was integrated over each of the regions inside the toroidal field coil to obtain a properly averaged value of the gross MHD effect. The pressure loss in each region was then determined[2,4] using the corresponding average value of $B^2$ for that region. Because the actual lengths of the coolant flow paths, the sizes of the inlet and outlet headers, and the locations of bends, fittings, etc. for a commercial reactor are subject to considerable uncertainty, a safety factor of two was employed in calculating each pressure drop. The thicknesses of the inlet piping to the blanket cell, the cell wall itself, and the manifolds were calculated based on the stress requirements corresponding to the prevailing operating conditions (temperature and pressure) with the assumptions that (a) the pressure stress cannot exceed one-third the yield strength[3] and (b) the wall thicknesses cannot be less than 2.5 mm in the blanket region and 5 mm in the shield and magnet regions due to fabrication constraints.

The heat transfer calculations for the flowing lithium concept (Fig. 1) were performed using standard empirical equations.[2,4] A one-dimensional steady-state analysis was carried out by dividing the blanket cell into (a) inlet piping, (b) first wall, (c) cell annulus and (d) cell side walls (see Fig. 1). These calculations were used to set the required coolant velocity for a given wall loading and to establish the general thermal characteristics of the system. The overall heat balance was determined based on a given wall loading due to (a) particles and radiation that create a first-wall surface flux and (b) neutrons that create internally generated heat. As the particle and surface radiation power fraction depends on whether the reactor has a divertor or not, two cases were considered — the particle and surface radiation loading factor was set equal to 25% of the neutron wall loading without divertor and 10% of the wall loading with divertor.




$$P_{max} = \Delta P_{MI} + \Delta P_{SI} + \Delta P_{BI} + \Delta P_{BO} + \Delta P_{SO} + \Delta P_{MO} + \Delta P_{ext} + P_{min}$$

$$P_{BC} = \Delta P_{BO} + \Delta P_{SO} + \Delta P_{MO} + \Delta P_{ext} + P_{min}$$

Figure 3. Pressure Drop Diagram for the Lithium Cooled Blanket Cells.

### Helium Cooled Stagnant Lithium First Wall/Blanket Concept

The thermal hydraulic analyses of a helium cooled tubular first wall coupled to a stagnant lithium blanket were based on the configuration shown in Fig. 2. The first wall is assumed to be made of a single row of tightly packed tubes and the blanket is in essence a "sea" of lithium extending radially outward from the back of the first wall and having an appropriately dispersed array of helium carrying tubes. A realistic boundary condition is set up so that there is no discontinuity in the thermal hydraulic analyses at the first wall/blanket interface. The radiation power deposited on the first wall and the nuclear heat generated within zone 1 (see Fig. 2) are removed by the helium flowing through the first wall tube bundle. Zone 2 (blanket) is divided into several regions and the number and size of the coolant tubes throughout these regions are calculated based on the internal heat generation rate so that the coolant exit temperatures for all regions are the same. Since the wall loadings (both radiation and neutron) were assumed to be constant along the coolant flow direction, the temperature difference between the wall and the coolant remains essentially constant, and the maximum wall temperature can be based on the coolant exit temperature. (Internal heat generation in the helium was assumed to be zero.) The thermal hydraulic calculations are carried out for each zone separately, with the assumption of an isothermal boundary at the zone 1/zone 2 interface. The criteria for materials property limitations were the same as those described above for the lithium cooled blanket concept.

## Results and Discussion

### Thermal Hydraulic Analyses of the Flowing Lithium Cooled First Wall/Blanket Concept

Typical results of thermal hydraulic analyses for four reference cases (stainless steel with and without a divertor and vanadium alloy with and without a divertor) are summarized in Table 2 and are presented in greater detail in references 2 and 4. For stainless steel (with or without a divertor) the maximum neutron wall loading generally occurs at relatively low wall thicknesses (i.e. ≤ 2.5 mm) and is limited by the thermal stress criterion (maximum thermal stress = material yield strength). For vanadium alloys this maximum occurs at somewhat larger wall thickness values

Table 2. Results of Wall Loading Trade Studies for Lithium-Cooled Stainless Steel and Vanadium-Alloy Blanket Systems[a]

| Criteria | | Li-Cooled V Alloy | Li-Cooled SS |
|---|---|---|---|
| Maximum Allowable Temp., °C | | 650 | 500 |
| Maximum Thermal Stress, MPa | | 351 | 117 |
| Minimum Wall Thickness, mm | | 2.5 | 2.5 |
| Maximum Wall Thickness, mm | | 8.0 | 8.0 |
| Minimum Coolant Inlet Temp., °C | | 235 | 235 |
| Coolant Temperature Rise, °C | | 325 | 225 |
| Maximum Neutron Wall Loading, MW/m$^2$ | | | |
| F[b] = 0.10 | 8 Tesla | 11.2[c] | 4.2[d] |
| | 10 Tesla | 7.5[e] | 3.5[d] |
| | 12 Tesla | 5.3[e] | 3.0[d] |
| F[b] = 0.25 | 8 Tesla | 8.0[c] | 2.0[d] |
| | 10 Tesla | 6.2[c] | 2.0[d] |
| | 12 Tesla | 4.6[c] | 1.8[d] |

a. For a cell diameter of 0.5 m and an inlet tube diameter of 0.1 m.

b. F = Fractional power loading on first wall surface due to particle and radiation effects.

c. Limited by minimum coolant inlet temperature criterion.

d. Limited by maximum thermal stress criterion.

e. Limited by MHD pressure stress criterion (i.e. maximum cell wall thickness insufficient to support higher coolant velocity).

(3 to 6 mm) and is limited by the minimum coolant inlet temperature criterion. The values of the maximum allowable neutron wall loading for 8, 10, and 12 T maximum toroidal fields are listed in the lower half of Table 2. The total pressure drops were nominally in the range from 3 to 6 MPa (including the safety factor of 2.0 on all calculated pressure losses).

The effect of maximum toroidal field and cell wall thickness on the maximum allowable neutron wall loading is illustrated more clearly in Figs. 4 and 5 for the four cases described above. As can be seen in Figs. 4 and 5 and in Table 2, there is some advantage (in terms of overall thermal hydraulic performance) to having the lower toroidal fields. For most cases, the actual advantage is in fact even greater than is indicated in Table 2, because the increased cell wall thicknesses required to support the maximum neutron wall loading at the higher toroidal fields have the concommitant effect of reducing the coolant exit temperature.

Early trade-off studies on the coolant temperature rise showed that the values in Table 2 (i.e. 225°C for stainless steel and 325°C for vanadium alloy) are near to optimum for each material based on the thermal-hydraulic model and maximum structural temperature limits used herein. Also, the pumping power to thermal power ratio (based on geometrically averaged values of the actual magnetic field strength inside the reactor) was found to be < 1.0, < 1.5 and < 2.0% for maximum toroidal fields of 8, 10 and 12 T, respectively.

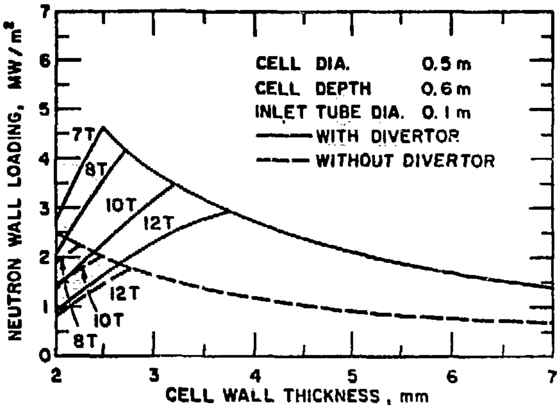



Figure 4. Effect of Cell Wall Thickness and Maximum Toroidal Field on Maximum Allowable Neutron Wall Loading for the Lithium Cooled Stainless Steel Blanket Cell.

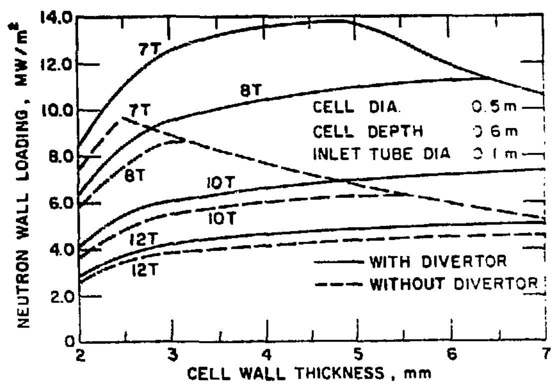



Figure 5. Effect of Cell Wall Thickness and Maximum Toroidal Field on Maximum Allowable Neutron Wall Loading for the Lithium Cooled Vanadium Alloy Blanket Cell.

Several cases were analyzed for effect of varying the size of the inlet piping to the blanket module while keeping the blanket cell size constant (e.g. cell diameter = 0.5 m). The thermal hydraulic results were found to be rather insensitive to small changes in inlet tube diameter since only the pressure drop from the inlet tube back is affected by this parameter. It can be easily shown that the size of the blanket cell cannot be varied over a wide range, although a cell diameter of 0.5 m is not necessarily the optimum. Increasing the cell diameter in order to reduce the number of modules required leads to larger cell wall thicknesses with resultant higher thermal stresses and lower coolant exit temperatures. A reduced cell size has the beneficial effect of lower wall thickness and lower thermal stresses, however, it increases the number of cells required for a given geometry. It may be noted that for the reactor size selected for this analysis, more than 5000 of the 0.5-m diameter cells would be needed. Since this is already a very large number, there is little incentive to go to a larger number of smaller modular units.

For stainless steel, which is usually found to be thermal stress limited, doubling the thermal stress limit tends to double the maximum allowable neutron wall loading and raising the upper operating temperature limit by 100°C increases the coolant exit temperature by an approximately equal increment. Increasing the upper operating temperature for vanadium by 100°C increases the maximum allowable wall loading but not the coolant exit temperature. However, for a given wall loading, it is always possible to achieve a higher coolant exit temperature with a higher upper operating temperature value.

Data of the type presented in references 2 and 4 have permitted the derivation of a series of empirical equations which relate the coolant exit temperature, T(CE), to maximum material temperature, T(MAX), neutron wall loading $Q_N$, and cell wall thickness, t for each of the material and divertor options investigated. For stainless steel

$$T(CE) = T(MAX) - t\ [1.2\ Q_N + 0.5]\ \text{with divertor}$$

and

$$T(CE) = T(MAX) - t\ [\frac{T(MAX) - 400}{100}]\ [1.3\ Q_N + 0.25]$$

without a divertor.

For vanadium

$$T(CE) = T(MAX) - t\ [\frac{T(MAX) - 400}{100}]\ [2.0\ Q_N - 3.8]$$

with divertor and

$$T(CE) = T(MAX) - t\ [\frac{T(MAX) - 400}{100}]\ [2.0\ Q_N - 3.8]$$

without divertor.

Only in the case of stainless steel with a divertor present did the value of T(MAX)-T(CE) show negligible dependence on the value of T(MAX). In the other three cases the empirically derived function [T(MAX) - 400]/100 had to be employed to reconcile the calculated T(CE) values.

Thermal Hydraulic Analyses of the Helium Cooled Stagnant Lithium First Wall/Blanket Concept

One of the primary objectives of the thermal hydraulic analysis for the helium cooled stagnant lithium concept was to make the coolant operating parameters and characteristics reasonably consistent with existing HTGR experience.[5] Table 3 contains a summary of results with stainless steel as construction material and with the following sets of conditions: (a) the presence of or absence of a divertor, (b) maximum allowable structural temperatures of 500° or 650°C, (c) thermal stress limits of 17 or 34 ksi, and (d) heat transfer coefficient and friction factor multipliers of 2.2 and 4.0, respectively.[5] The asterisked parameters in Table 3 were fixed in the calculation and the primary iteration was done by increasing the neutron wall loading until the thermal stress limit at the first wall was exceeded.

In the thermal hydraulic analysis of the first wall, the coolant velocity is fixed at 200 ft/s, the tube diameter is fixed at 25.4 mm (1 inch), and the tube wall thickenss is not allowed to be less than 1.25 mm (50 mil). In the thermal hydraulic analysis of the blanket, the coolant void fraction, VF, is fixed at 5% and the temperature drop through the lithium ΔT(Li), is set at 25°C. Trade studies on the latter two parameters have been completed for VF = 5, 7, and 10% and ΔT(Li) = 25, 50, and 100°C. These studies show that, in terms of maximum coolant exit temperature, VF = 5% and ΔT(Li) = 25°C are closer to optimum than the other values tested. Other parameters that were fixed in these analyses are given in Table 3. The coolant exit temperature, from the first wall region, T(CE), may be represented empirically in terms of the neutron wall loading, $Q_N$, and the maximum allowable structural temperature, T(MAX), by

$$T(CE) = T(MAX) - 17.9 \cdot Q_N - 21.9\ \text{(with divertor)}$$

$$T(CE) = T(MAX) - 41.3 \cdot Q_N - 21.4\ \text{(without divertor)}.$$

The coolant exit temperature from the blanket region is nominally 30 to 50°C below the maximum structural temperature and seems to be relatively independent of wall loading or divertor status.

The values arrived at in Table 3 are based largely on attempts to control thermal stress and peak structural temperature, and as a result do not reflect optimum performance from the standpoint of coolant exit temperature. In particular, the cases where the coolant exit temperature from the first wall or the blanket is < 500°C probably do not represent economically attractive systems. Figures 6 and 7 show how these coolant exit temperatures are affected by backing down from the maximum neutron wall loading values given in Table 3 for the 500°C and 650°C stainless steel operating temperatures. Based on these results the helium cooled stagnant lithium blanket would appear to achieve economic attractiveness at wall loading values considerably lower than those in Table 3 and at structural temperatures ≥ 600°C.

The principal indications from this study are that (a) T(MAX) ≥ 600°C is essential for useful T(CE) with helium, i.e., T(CE) > 500°C; (b) without a divertor $Q_N$ is limited to 2 to 5 $MW/m^2$, depending on allowable thermal stress level (ignoring, of course, the effects of fatigue and crack propagation for the time being); (c) in principal, considerably higher wall loadings can be achieved with a reasonably effective divertor; (d) fabrication of the first wall out of 50-mil tubing is assumed to be feasible (if the limit were 100 mil, the allowable $P_w$ values would drop by a factor of 2); and (e) the number of tubes and gross tube weights for a reactor with a first wall area of ~ 1000 $m^2$ are extremely large.

Application of the multiplier factors for the heat transfer coefficient and frictional pressure drop is based on the assumption that the interior tube walls can be roughened or otherwise modified to augment heat transfer with a resulting modest impact on the pressure drop. Omission of these multiplier factors (i.e., equating them to unity) generally results in substantial increases in coolant velocity (to > 400 ft/s) and channel length (70 to 80%) with somewhat smaller reductions in heat transfer coefficient (~ 30%) and coolant exit temperature (4 to 5%).

## Conclusions

Because studies of the type described in this report tend to "idealize" the complicated geometry and widely-ranging operating conditions of potentially attractive tokamak-type fusion reactors, any conclusions drawn from them should be interpreted carefully and not arbitrarily extrapolated to fusion power systems in general. The key conclusions from the study of the liquid lithium cooled first wall/blanket concept may be summarily stated as follows: (a) The maximum allowable neutron wall loading for a given reactor design

Table 3. Trade Study for Helium Cooled Stagnant Lithium Blanket Using Transverse Cooling Channels Made of Stainless Steel: First Wall Configuration is a Single Layer of Closed-Packed Tubes.
(* Indicates fixed or independant parameter)

| Divertor Option | With Divertor | | | | Without Divertor | | | |
|---|---|---|---|---|---|---|---|---|
| **General Parameters** | | | | | | | | |
| * Maximum Structural Temp., °C [T(MAX)] | 500 | | 650 | | 500 | | 650 | |
| * Helium Inlet Pressure, ksi | 1.0 | | 1.0 | | 1.0 | | 1.0 | |
| * Pump Power/Thermal Power, % | 5 | | 5 | | 5 | | 5 | |
| * Coolant ΔT, °C | 200 | | 300 | | 200 | | 300 | |
| * Lithium ΔT, °C [ΔT(Li)] | 25 | | 25 | | 25 | | 25 | |
| Neutron Wall Loading, MW/m² | 6.2 | 12.4 | 6.0 | 12.0 | 2.6 | 5.3 | 2.6 | 5.1 |
| **First Wall Parameters** | | | | | | | | |
| * Helium Tube Dia., mm | 25.4 | | 25.4 | | 25.4 | | 25.4 | |
| * Helium Velocity, ft/s | 200 | | 200 | | 200 | | 200 | |
| * Thermal Stress, ksi | 17 | 34 | 17 | 34 | 17 | 34 | 17 | 34 |
| Wall Thickness, mm | 1.25 | | 1.25 | | 1.25 | | 1.25 | |
| Channel Length, m | 12.2 | 13.2 | 17.3 | 18.5 | 12.2 | 13.1 | 17.3 | 18.4 |
| HT. TR. Coeff., BTU/hr.ft.²°F | 1693 | 1980 | 1510 | 1729 | 1679 | 1968 | 1507 | 1720 |
| Coolant Inlet Temperature, °C | 171 | 61 | 217 | 105 | 173 | 67 | 220 | 110 |
| Coolant Exit Temperature, °C [T(CE)] | 371 | 263 | 517 | 405 | 373 | 267 | 520 | 410 |
| Wall ΔT, °C | 53 | 106 | 50 | 100 | 53 | 107 | 50 | 100 |
| No. of Tubes, Hundreds[a] | 32 | 29 | 22 | 21 | 32 | 30 | 22 | 21 |
| Total Tube Weight, Tons[a] | 35 | | 35 | | 35 | | 35 | |
| **Blanket Parameters** | | | | | | | | |
| * Void Fraction, % [VF] | 5 | | 5 | | 5 | | 5 | |
| Tube Diameter, mm | 4.9 | 3.4 | 5.2 | 3.6 | 7.7 | 5.4 | 8.2 | 5.8 |
| Wall Thickness, mm | 0.41 | 0.37 | 0.42 | 0.37 | 0.48 | 0.43 | 0.49 | 0.43 |
| Channel Length, m | 1.1 | 0.6 | 1.5 | 0.8 | 2.3 | 1.3 | 3.3 | 1.8 |
| HT. TR. Coeff. BTU/hr.ft.²°F | 2541 | 2981 | 2361 | 2769 | 2068 | 2427 | 1924 | 2253 |
| Helium Velocity, ft/s | 251 | 276 | 263 | 290 | 220 | 244 | 231 | 255 |
| Coolant Inlet Temperature, °C | 259 | 249 | 305 | 295 | 268 | 261 | 316 | 308 |
| Coolant Exit Temperature, °C | 459 | 449 | 605 | 595 | 468 | 461 | 616 | 608 |
| Wall ΔT, °C | 8.0 | 11.1 | 8.0 | 10.0 | 6.0 | 8.0 | 6.0 | 8.0 |
| Thermal Stress ksi | 2.7 | 3.4 | 2.6 | 3.4 | 2.0 | 2.5 | 1.9 | 2.5 |
| No. of Tubes, Thousands[a] | 939 | 3435 | 585 | 2149 | 174 | 644 | 109 | 398 |
| Total Tube Weight, Tons[a] | 74 | 96 | 71 | 91 | 54 | 69 | 52 | 66 |

[a] Based on a reactor with a first wall area of ~ 1000 m²

$T(CE) = T(MAX) - 17.9\, P_w - 21.9$

$T(CE) = T(MAX) - 41.3\, P_w - 2$[illegible]

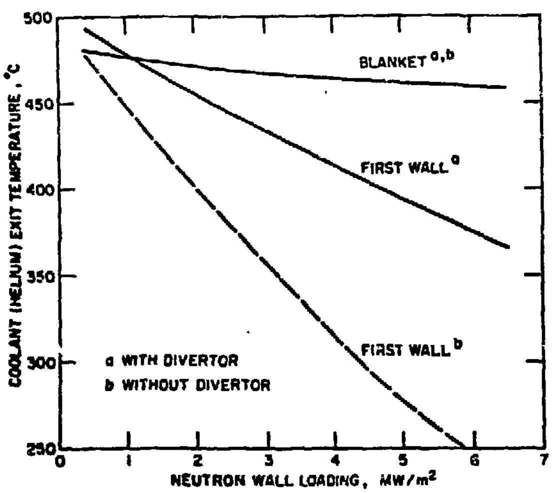



Figure 6. Coolant Exit Temperature versus Wall Loading for the Helium Cooled Stagnent Lithium Blanket (maximum structural temperature = 500°C).

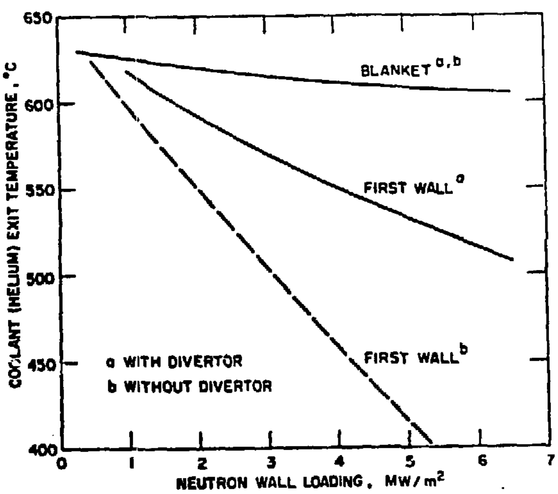



Figure 7. Coolant Exit Temperature versus Wall Loading for the Helium Cooled Stagnent Lithium Blanket (maximum structural temperature = 650°C).

can be increased from 40 to ~ 90% by the addition of a divertor. The magnitude of the increase depends primarily on which criteria set the maximum wall loading, e.g., increases tend to be greatest in thermal stress limited systems. (b) With respect to overall thermal hydraulic performance, austenitic alloys will tend to be thermal stress limited, whereas vanadium-base alloys will be limited by the pinch between maximum allowable structural temperature and minimum coolant inlet temperature. (c) Significantly higher neutron wall loadings appear to be achievable with vanadium alloys than with solution annealed 316-SS. (d) Ignoring the application of advanced power conversion cycles, there is little incentive for structural temperatures in excess of 650°C, since the associated coolant (lithium) exit temperatures( ≥ 550°C) are more than adequate to drive optimized steam turbine cycles. (e) Overall design and performance objectives for lithium cooled reactors will be more easily met at lower toroidal fields (8 to 9 T). Fields as high as 12 T may preclude the use of circulating lithium in all but the most outboard regions of the blanket.

For the case of the helium cooled stagnant lithium first wall/blanket concept, the key conclusions are as follows: (a) A maximum allowable structural temperature ≥ 600°C will be necessary to assure the attainment of attractive operating conditions (i.e., reasonable thermodynamic efficiency) for the helium coolant. (b) As in the case of the lithium cooled first wall/blanket concept, the presence of a divertor increases the allowable wall loading by nearly a factor of two in thermal stress limited systems. (c) The transverse cooling arrangement employed in the helium cooled concept (Fig. 2) requires an enormous number of individual tubes and is probably less attractive (from the standpoint of fabricability and overall thermal hydraulic performance) than the radially cooled helium blanket concept described by Kearney, et al.[6]. (d) There appears to be some incentive to provide for augmentation of the heat transfer coefficient in helium cooled reactors, even though this will undoubtedly be accompanied by increased pressure losses.

Finally, it must be noted that the studies described herein consider only steady-state performance of the first wall/blanket system, and as a result the derived operating conditions (wall loadings, coolant exit temperatures, etc.) represent upper limits to the performance of an actual system. In the long run, the effects of thermal strain and cyclic fatigue will act to reduce the allowable wall loading and in all likelihood, the peak allowable structural temperature as well. This contention is supported by the more recent work of Majumdar and Misra[7,8] on the fatigue life modeling of the lithium-cooled module in Figure 1.

## Acknowledgements

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