The MHD pressure losses as a possible criterion for the selection of structure materials for fusion reactor blankets

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The MHD pressure losses as a possible criterion for the selection of structure materials for fusion reactor blankets (in English)

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Abstract

In the present stage of fusion reactor development no decision can be made concerning the optimum structure material to be used in the blanket region. This paper deals with a comparison of four candidate materials in view of the effects caused by MHD pressure losses. The differences in the material properties, especially the electrical and mechanical properties, thereby lead to a different choice dependent on the coolant temperature range and on the criterion used.

The investigation shows that all materials considered - stainless steel, vanadium, niobium, and molybdenum - have chances if the absolute pressure drop is the quantity of interest. Only vanadium and molybdenum remain in consideration if the amount of material is essential. If the costs will be the determining quantity it seems possible that the selection will only yield stainless steel and molybdenum as the most advantageous materials.

1. Introduction

Within the last few years a change has taken place in the discussion about the most suitable structure material for fusion reactor blankets. Whereas for a long time the refractory alloys on niobium base have been favoured a larger series of other materials is now under consideration.

Table I presents a summary of the today's candidate materials together with a rough qualification of the knowledge about those properties being essential for this special application. Besides niobium and molybdednum as the originally preferred metals also vanadium and austenitic stainless steels have meanwhile been investigated. For special concepts furthermore nickel base alloys and aluminum are discussed.

Table I: State of Knowledge (1973) on Material Problems for Liquid Lithium Blankets

Problems	Materials (Alloying base)					
	Nb	Mo	V	Fe	Ni	Al
Neutron Economy	good	good	good	good	good	good
Activation	high	high	medium	medium	?	low
Mechanical Properties under Irradiation	?	few data	few data	much data	much data	?
Corrosion limit	>1000 C	>1000 C	800 C	500-600 C	bad	bad
Tritium-Permeation	high	low	high	low	medium	?

The problems of neutron economy especially with regard to a sufficient tritium breeding ratio can be solved for each of these materials. The activation behaviour of all materials except the nickel base alloys has also been investigated. The accuracy of these results, however, is not too good because of the limited knowledge about the relevant cross-section data. The advantageous activation properties of aluminum, by the way, have given rise to consider just this material. There are only very few data concerning the behaviour of the mechanical properties in a radiation environment. The most complete knowledge is available for the stainless steels and nickel base alloys. The latter ones, however, can not be used in a liquid lithium blanket; they are of interest only for concepts incorporating Li_2BeF_4 (FLIBE) molten salt cooling or - as is likewise the case for aluminum - helium cooling in connection with a solid blanket. The last item in the table is the problem of tritium permeation. Although a lot of work is still being done the differences between the single materials are qualitatively rather well known.

The possibility to state criteria for a selection among these materials requires basic investigations of the materials properties on the one hand and extensive system studies on the other hand to find out the influence of the bulk of all properties upon the layout of a fusion reactor blanket. To a certain degree, however, criteria can be found already by investigating special subsystems or single but important effects. One of those effects is, for instance, the MHD-pressure loss which is a significant design parameter for those liquid metal blankets which make use of the lithium as the heat carrier to the external cycle components. In the following it shall be explained in which way it is possible to arrive at certain criteria with respect to this effect and which results are to be expected.

2. The material dependency of MHD-pressure losses

In a fusion reactor the thermonuclear plasma will be confined by a magnetic field which with great probability will be created by superconducting coils. These coils represent the outermost region of the toroidal reactor, the blanket will therefore be situated inside the magnetic field.

Undoubtedly it is an advantage of a liquid blanket that the lithium is not only the medium in which the heat will be produced but that it can also be used as the coolant. The maximum temperature of the thermal power cycle, therefore, differs only slightly from that temperature at which the thermal energy is produced. That is the reason why in principle very high efficiencies will be possible.

The choice of this cooling principle - the so called direct cooling method - involves the complication that due to the high electrical conductivity of liquid metals MHD-pressure losses occur additionally to the hydrodynamic pressure losses in the coolant circuit. These MHD-losses which are produced by the interaction of the liquid metal flow with the magnetic field can exceed the hydrodynamic losses by far.

Fig. 1 shows in its lower part the total pressure drop in the circuit of a single blanket cell as it was presented by MITCHELL and HANCOX [1].

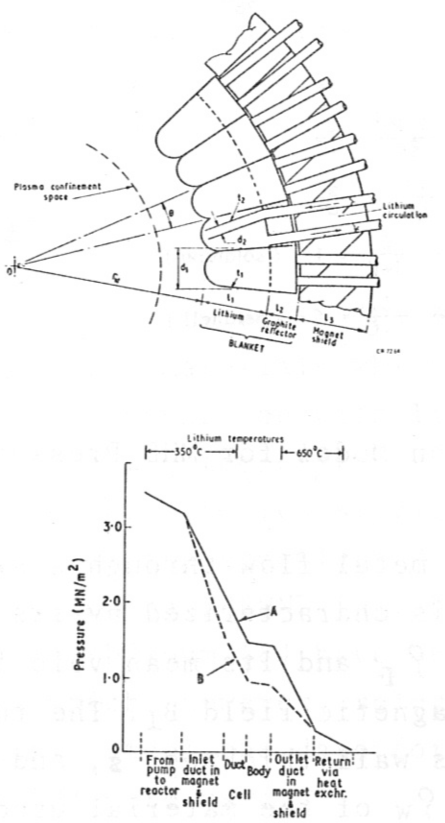
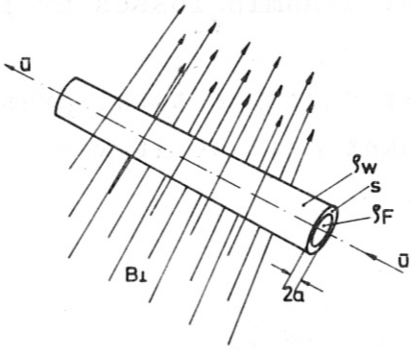


Fig. 1: Blanket Assembly and Pressure Drop for the Culham Conceptual Design

The whole blanket is assembled, as shown in the upper part of the picture [2], by a large number of such modules. From the diagram it can be recognized that the biggest part of the total pressure drop is to be expected in the inlet and outlet ducts of the cell which penetrate the rather thick shield region. Just this is the region the present paper deals with in order to quantify the materials influence upon the pressure drop in these tubes.

In Fig. 2 the main features of the calculation model and the governing equations are summarized.



$$\frac{dp}{dx} = \frac{\bar{u} \cdot B_{\perp}^2}{\varrho_F} \cdot \frac{C}{1+C}$$

$$C = \frac{\varrho_F}{\varrho_W} \cdot \frac{s}{a}$$

$$C \gg 1 \longrightarrow \frac{C}{1+C} \approx 1 \quad \text{(Isolatoren)}$$

$$C \ll 1 \longrightarrow \frac{C}{1+C} \approx C \quad \text{(Metalle)}$$

Fig. 2: Calculation Model for MHD Pressure Loss

For the model a liquid metal flow through a straight tube is considered. The fluid is characterized by its specific electrical resistivity ϱ_F and its mean velocity $\bar{u}$ normal to the direction of the magnetic field $B_{\perp}$. The tube is defined by its diameter 2a, its wall thickness s, and the specific electrical resistivity ϱ_W of the material used. If the fluid is in direct contact with the wall eddy currents are induced the paths of which will be closed in the conducting wall. As a consequence body forces are acting on the fluid which are the reason for the enhanced pressure drop.

Due to HOFFMAN [3] this MHD-pressure drop can be described by the equation:

$$\frac{dp}{dx} = \frac{\bar{U} \cdot B_{\perp}^{2}}{\rho_F} \cdot \frac{C}{1 + C} \tag{1}$$

Here C is the so called wall conductance ratio defined by

$$C = \frac{\rho_F}{\rho_W} \cdot \frac{s}{a} \tag{2}$$

This quantity can be conceived as a materials characteristic related to a specific fluid. It is determined by the electrical properties of the fluid and the wall material and by the mechanical properties of the wall since the mechanical strength decides upon the ratio of s/a. In the case of metallic tube materials C is generally $C \ll 1$ [3, 4]. That means that the pressure drop due to equ. (1) is in first approximation directly proportional to C.

3. The resistivity ratio

Fig. 3 shows the resistivity ratio ρ_F / ρ_W as a function of temperature for the four materials which, due to table I, are applicable for use in connection with liquid lithium. In calculating this ratio the temperatures of the fluid and the wall have been set equal. The resistivity data for liquid lithium were taken from the excellent data summary on liquid alkali metals published by FREUND [5]. Data on niobium [6], vanadium [7], and molybdenum [8] have been found in the Russian literature which, however, refer to nearly pure metals. For stainless steel the data for type 316 SS published by GOLDSMITH e.a. [9] were used.

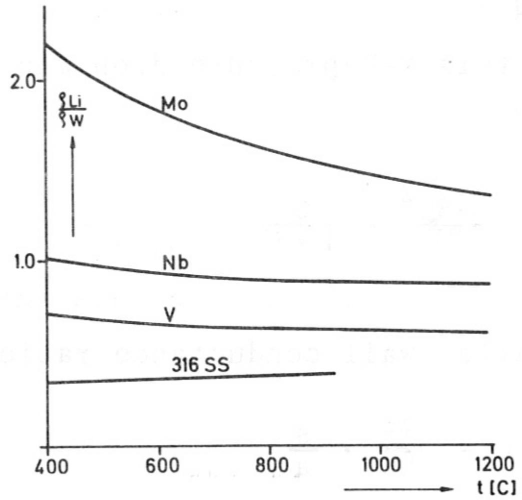


Fig. 3: Resistance Ratio vs. Temperature

Due to fig. 3 the most advantageous material with regard to a low pressure drop would be stainless steel, followed by vanadium and niobium. The largest values can be expected by use of molybdenum.

4. The mechanical properties

The second factor in equ. (2) is the ratio of wall thickness and tube radius which is determined by mechanical properties. To fix the mechanical properties necessary for this investigation is rather difficult because it is not possible to select a certain alloy just now. Furthermore there is no sufficient knowledge about the irradiation effects on the mechanical properties at least for the refractory alloys considered here. In spite of this situation it was tried to fix some data keeping in mind that this investigation should only be understood as a model.

At first it is assumed that the tube is exclusively loaded by a static internal pressure causing tensile stresses in the wall material. Thermal stresses caused by temperature gradients inside the wall are therefore neglected. In this case the simple equation can be applied:

$$\frac{s}{a} = \frac{p}{\sigma} \qquad (3)$$

which says that the ratio of wall thickness and tube radius is equal the ratio of the internal pressure and the tensile stress. For equal pressures p the ratio of s/a therefore becomes the smaller the higher the permissible tensile strength $\bar{\sigma}$ can be chosen. The determinative strength in that case should be the time-rupture-strength.

Fig. 4 shows the ranges of the 10 000 hour time-rupture-strength for the alloy systems considered here as a function of temperature, as it has been published in [10].

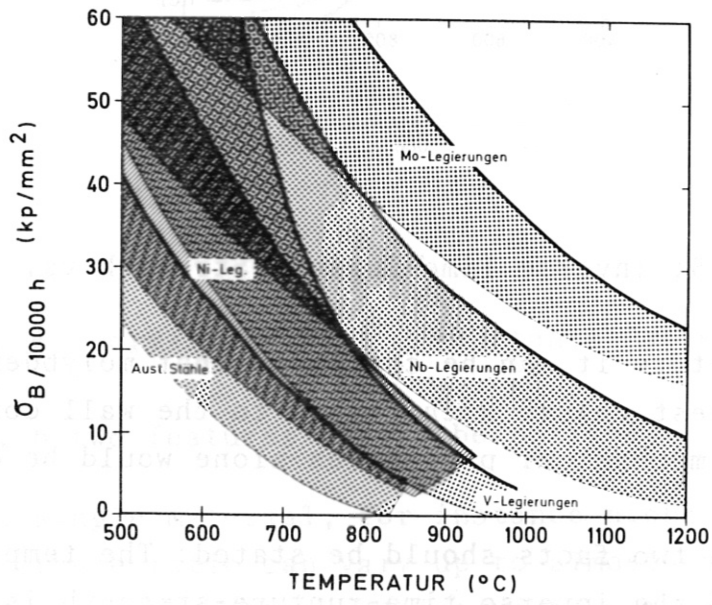


Fig. 4: 10^4h-Time-Rupture-Strength vs. Temperature

Due to this picture the highest values can be expected by use of molybdenum, the lowest by use of stainless steels. Because of a lack of data for special alloys in the following reference is made always to the lower limit of the equivalent ranges.

With regard to the wall conductance ratio for our purpose the reciprocal value of the time-rupture-strength is of interest. In Fig. 5 the inverse of the time-rupture-strength is plotted against the temperature.

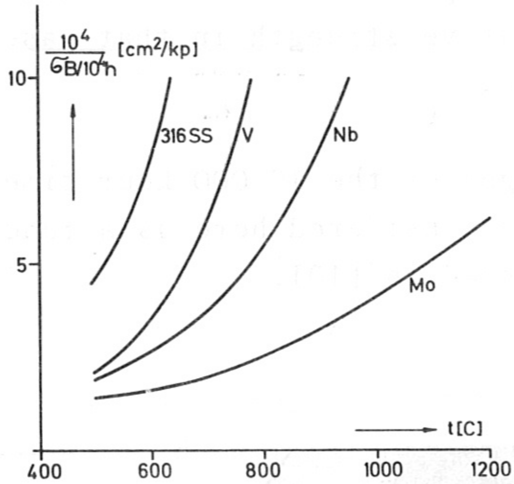


Fig. 5: Inverse Time-Rupture-Strength vs. Temperature

From this picture it can be concluded that molybdenum would yield the lowest values with regard to the wall conductance ratio if the mechanical properties alone would be considered.

At this point two facts should be stated: The temperature dependence of the inverse time-rupture-strength is more significant than that of the resistivity ratio. Furthermore, the material selection by use of one of the two properties would just be done in the reverse sequence than it would result by using the second property. From that fact it can be concluded that a combination of both properties could maybe yield optimum temperature ranges for one or another material.

5. The wall conductance ratio

By multiplying the resistively ratio and the inverse time-rupture-strength a normalized wall conductance ratio can be obtained. Fig. 6 shows the result of this product if the normalization is done with a value of p = 1 ata.

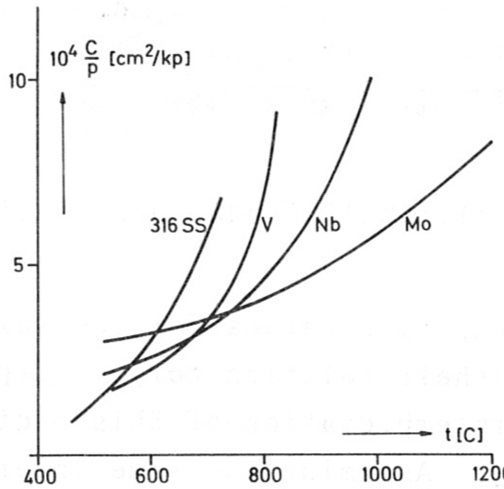


Fig. 6: Normalized Wall Conductance Ratio vs. Temp.

From fig. 6 two features should be noticed:

1. For a single material, for instance niobium, the wall conductance ratio can vary up to almost one order of magnitude within the most interesting temperature range between 500 C and 1000 C. This fact should stress the importance of a suitable material selection.

2. As was suspected earlier, for each of the alloy systems optimum temperature ranges exist in which they are superior to all of the other competitives.

The second fact can be recognized in a more pronounced way from fig. 7.

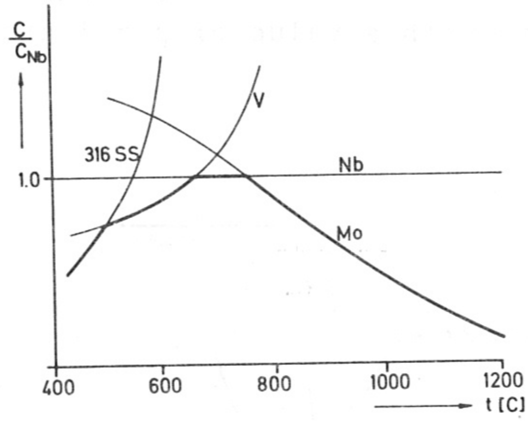


Fig. 7: Relative Wall Conductance Ratio vs. Temp.

In this picture the same values for the wall conductance ratio are shown but in their relation to the equivalent figures obtained for niobium. An interpretation of this picture can be done in the following way: Assuming the same internal pressure p for all cases the use of stainless steels would be preferable up to temperatures of about 500 C. The optimum range for vanadium alloys is to be expected for temperatures between 500 C and 700 C. Only between 700 C and 800 C niobium is the most advantageous material. At temperatures above 800 C only molybdenum should be used.

It is interesting to see that the limits resulting from this consideration are in very good agreement with the limits set by corrosion effects.

The criterion stated by this investigation was based upon the minimization of the MHD-pressure losses. This seems to be a useful criterion with regard to the absolute figures of the pressure drop evaluated for the concept shown in fig. 1. Together with the necessary mean flow rates such a pressure drop of 35 ata raises great difficulties, for instance, in the development of liquid metal pumps.

6. Material expense

Above the considerations on the selection criterion just described it seems possible that other criteria are more stringent. One of these could be the minimization of the material expense. This could be a requirement resulting from the investigation of neutron economy. In this case the product of wall conductance ratio C, the ratio of wall thickness and tube radius s/a, and the material density d is the significant quantity for comparison:

$$g \sim C \cdot \frac{s}{a} \cdot d \qquad (4)$$

If the previous considerations are extended to this aspect the results shown in fig. 8 are obtained.

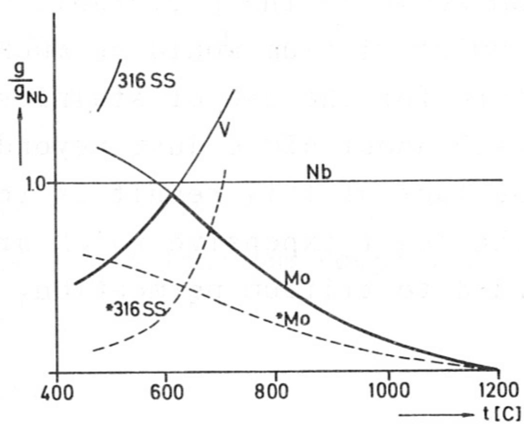


Fig. 8: Relative Material Expense vs. Temperature

As can be seen from the solid lines niobium and especially stainless steel become uninteresting in comparison with vandium and molybdenum. The temperature limit for the use of vanadium decreases to about 625 C, at higher temperatures only molybdenum remains with a strong increasing advantage if the temperature increases, too.

7. Influence of costs

The material expense is strongly coupled to the costs. Therefore also the costs could be taken as a criterion for material selection. Today it is unpossible to specify the specific costs of a vanadium-, niobium-, or molybdenum-alloy which will be valid at that time the selection will have to be made. The present cost situation will surely not be representative. If alloys of such kind will once have to be used the development of new techniques in production and fabrication will be necessary which will differ very much from the present ones.

Therefore, at this stage only a possible tendency shall be shown which results if certain cost-relationships are taken into account. If it is assumed that niobium and vanadium would be available at approximately the same costs, molybdenum and stainless steels, however, to half resp. a tenth of these costs, the curves for steels and molybdenum in fig. 8 would change to those represented by the dotted lines. This means that stainless steels and molybdenum would be the preferable materials whereas the use of vanadium or niobium would be much more expensive. The maximum temperature for the use of stainless steels, however, will then be with about 650 C just beyond the corrosion limit. An interesting fact of this result is that just those materials would be the least expensive which are the most appropriate with regard to tritium permeation.

8. Conclusions

For the selection of the most suitable structure material for fusion reactor blankets a series of aspects has to be taken into account. These aspects yield from the different specific properties of the materials under consideration. To make a decision in favour of one or another material criteria must be found which comprise as much of the relevant properties as possible.

The present investigation is concerned with only a few of them. For this reason and because of a series of uncertainties in the data assumed it should only be understood as a model.

To state criteria the consideration of the MHD-pressure losses was chosen in this investigation. This is an important quantity for liquid lithium blankets by application of the direct cooling principle. The results show that in different temperature ranges also different materials offer as the optimum choice. This selection, however, is not unique. It depends essentially on the formulation of the criterion. As a special result the investigation shows that the originally preferred niobium must not necessarily be the optimum material.

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