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Bericht der Working Group MHD für die Blanket Concept Selection Exercise (BCSE)

ZUSAMMENFASSUNG

Die Blanket Comparison and Selection Exercise (BCSE), die 1994 und 1995 durchgeführt wurde, hatte als Ziel, zwei der vier am besten erscheinenden europäischen DEMO Blanket Konzepte für die weitere Entwicklung und das Testen in ITER auszuwählen. In diesem Zusammenhang wurden 14 Working Groups gebildet, wobei jede einen bestimmten technischen Bereich behandelte. In diesem Bericht werden die Ergebnisse der Working Group MHD über die magnetohydrodynamischen Probleme der beiden Blanketkonzepte dargestellt, die das Flüssigmetall Pb-17Li verwenden: das Dual Coolant Blanket (DCB) und das Water-Cooled Blanket (WCB).
Zwei Designversionen beider Blankettypen wurden betrachtet: Die Referenzdesigns basieren auf einer elektrisch isolierenden Direktbeschichtung entweder auf der gesamten Oberfläche (DCB) oder einem Teil der Oberfläche (WCB) des Strukturmaterials, die in Kontakt mit Pb-17Li ist. In den Backup-Designs ist das Flüssigmetall in Kontakt mit metallischen Wänden (dem MANET Strukturmaterial im Falle des WCB und den Strömungskanaleinsätzen (FCI) beim DCB).
Die folgenden Problemkreise wurden identifiziert und im Detail analysiert: Druckverlust, Wärme- und Tritiumtransport sowie die Bildung und der Transport von Korrosionsprodukten. Als ein getrenntes Problem wird die Schädigung der Isolierung behandelt, die sowohl Druckverlust als auch Transportprozesse beeinflußt.
Jedem Problemkreis wurden Wichtungsfaktoren zwischen 1 und 10 zugeordnet und die individuellen Probleme der Blankets wurden mit Noten bewertet, die von "0" (nicht relevant) bis "-2" (beträchtliche Probleme oder Machbarkeit in Frage gestellt) reichten.

Für das DCB ist das kritische Problem die Isolatorschädigung. (Für FCIs kann das Problem etwas weniger schwerwiegend sein). Druckverlust (für intakte Isolierung) ist von mittlerer Bedeutung und erfordert weitere F&E-Arbeiten. Die anderen Problemkreise sind von untergeordneter Bedeutung.
Für das WCB sind alle Problemkreise von recht geringem Einfluß, was jedoch immer noch weitere F&E Arbeiten notwendig macht, um das Blanket zu optimieren. Ein Thema, das erwähnt werden soll, ist die freie Konvektionsströmung in der Blanketbox.

SUMMARY

The Blanket Concept Selection Exercise (BCSE) was performed between 1994 and 1995 with the objective to select two out of four of the most promising European DEMO blanket concepts for further development and testing in ITER. In this framework 14 working groups have been created each treating one particular technical aspect of the blankets. This report represents the result of the Working Group MHD on the magnetohydrodynamic issues of the two blanket concepts using liquid Pb-17Li, the Dual Coolant Blanket (DCB) and the Water-Cooled Blanket (WCB).

Two design versions of both blanket types were considered: The reference designs use an electrically insulating direct coating either on the total surface of the structural material (DCB) or on a part of the surface (WCB). In the back-up designs the liquid metal is in contact with metal walls (MANET structure in case of the WCB and Flow Channel Inserts (FCI) for the DCB).

The following issues have been identified and analysed in detail: pressure drop, heat transport, tritium transport, corrosion product generation and transport. As a separate issue, the degradation of insulation is included which comprises the effects on pressure drop and transfer processes.

Weighting factors between 1 and 10 were attributed to each criterion and scores for the evaluation of the individual issues were given ranging between "0" (not relevant) and "-2" (considerable problems or not suitable).

For the DCB, the critical issue is the degradation of insulation (for FCI`s this issue might be less severe). Pressure drop (for intact insulation) is of medium importance and requires future R&D work. The other issues are of minor importance.

For the WCB, all issues are evaluated to be of minor importance which, however, still necessitates R&D work in order to optimize the design. One topic to be mentioned is free convection flow within the blanket box.

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1. INTRODUCTION

1.1 MHD Issues of Liquid Metal Blankets

Magnetohydrodynamic (MHD) effects of liquid metal (LM) blankets can endanger the feasibility of these blanket types due to uncertainties in two areas:
Pressure drop: here, it has to be demonstrated that the pressure drops do not result in such a high system pressure that intolerable material stresses do occur. Furthermore, uneven pressure drops in parallel ducts must not deteriorate the cooling in some ducts due to reduced flow rates.
Velocity Distributions: local velocities determine the transfer mechanism for heat and mass (corrosion products, tritium). It must be proven that heat transfer from the walls is not deteriorated locally to such an extent that hot spots occur which can cause a premature structural material failure, that no excessive corrosion occurs and that no zones within the liquid metal exist where the tritium concentration becomes so large that tritium permeation losses become unacceptable.

The MHD issues of these two areas will be discussed in detail in Sections 2 and 3 for the two Pb-17Li blankets of interest, the Dual Coolant Blanket (DCB) /1.1, 1.2/ and the Water Cooled Blanket (WCB) /1.3, 1.4/. Then, the importance of the MHD issues is weighted for the individual concepts.

1.2 MHD Features of the two Pb-17Li Blankets

For the further understanding, the MHD features of the two blankets are briefly outlined.

Dual Coolant Blanket (DCB)

The description is given for the outboard blanket because, there, the MHD issues are most expressed (Figs. 1.1-1.4, from /1.1/). Two circular pipes are used both as inlet and outlet pipes between the y-pieces close to the flange covering the blanket exchange port (outside of the magnetic field) and the blanket box within the magnetic field. For the MHD analyses the inlet and outlet pipes of the lateral segments are considered because they are longer and include several bends. Each inlet pipe is connected with a distributing manifold feeding an array of 3x3 rectangular ducts where the LM flows downwards.

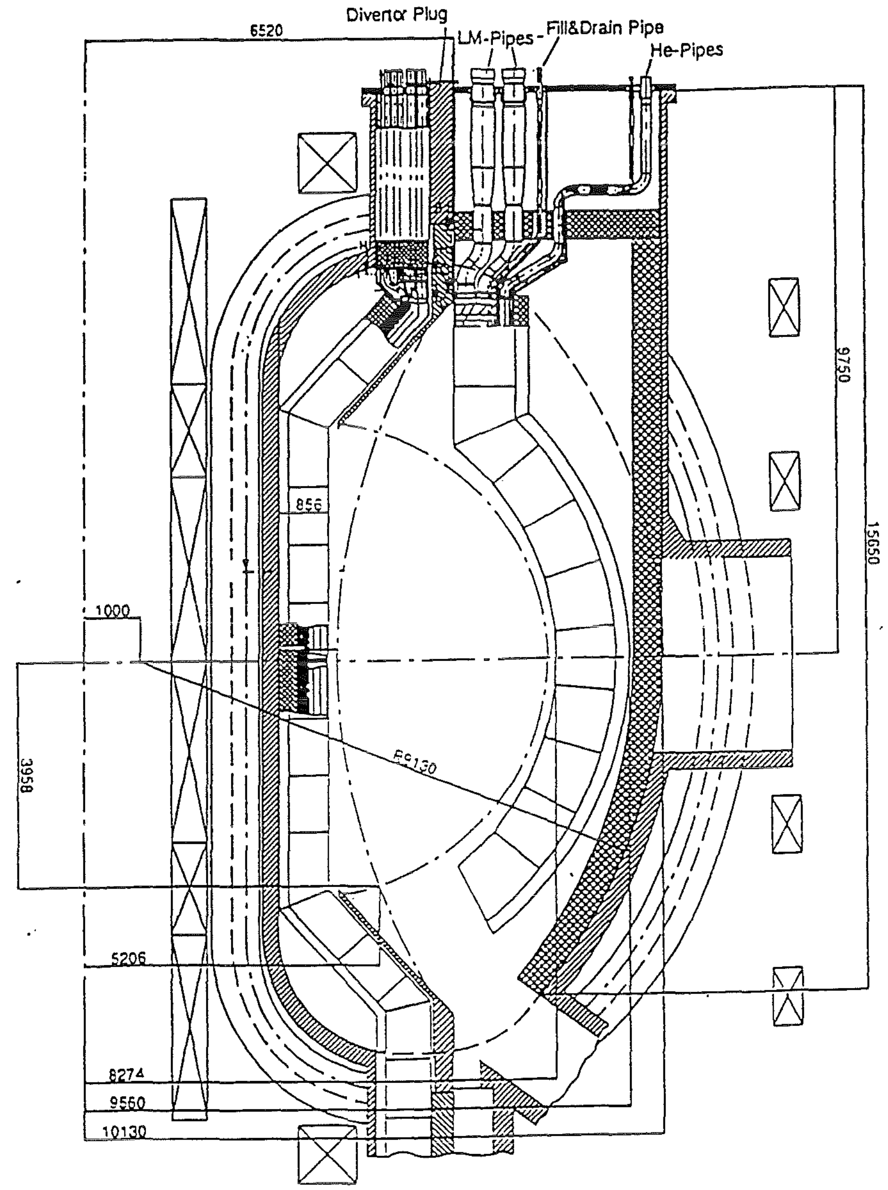


Fig. 1.1 Cross-section of the DEMO reactor with Dual Coolant Blanket (from /1.1/)

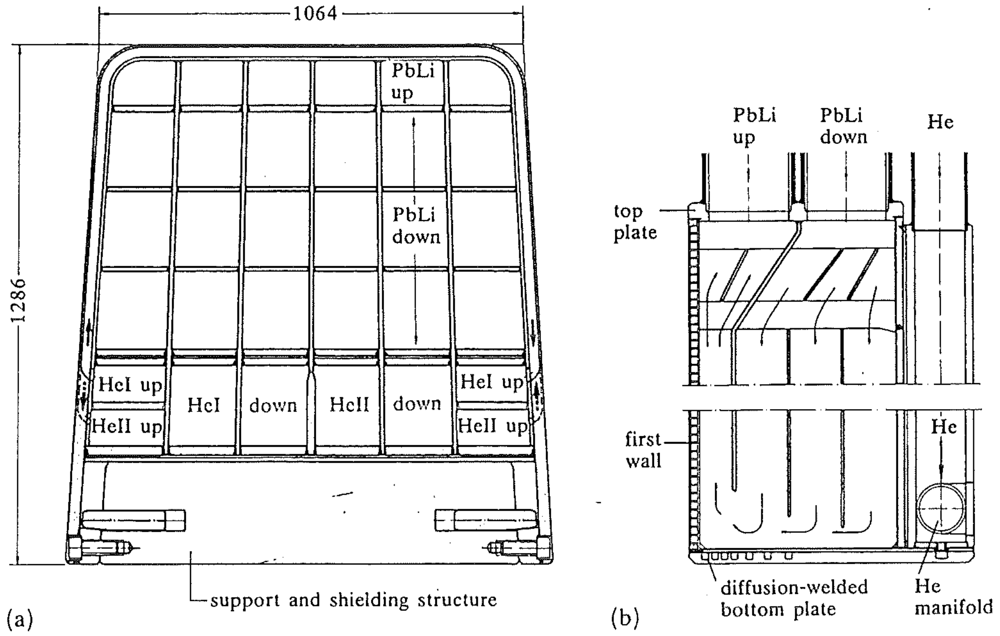


Fig. 1.2 (a) Cross-section of a dual-coolant blanket segment. (b) Upper and lower end of the dual-coolant blanket segment. Dimensions in mm. (from /1.1/)

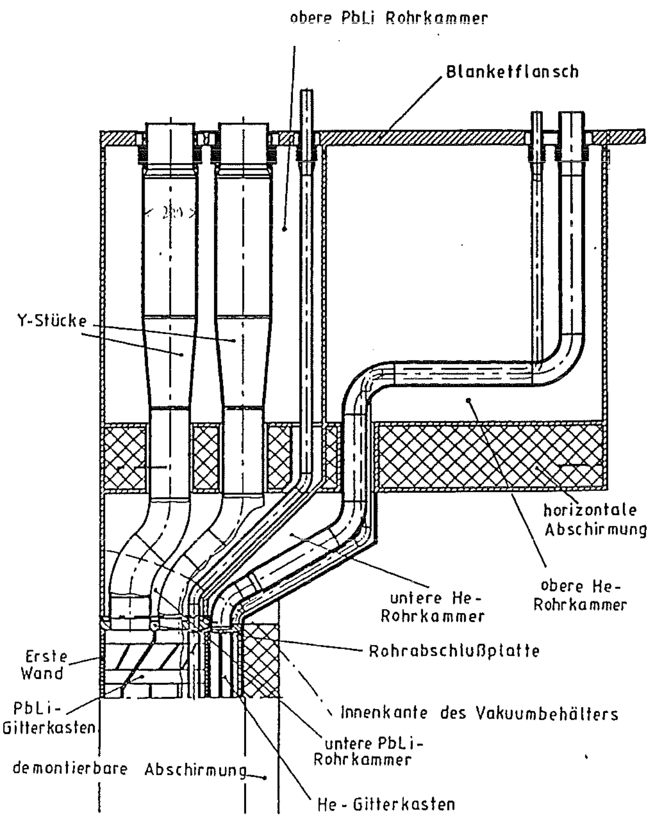
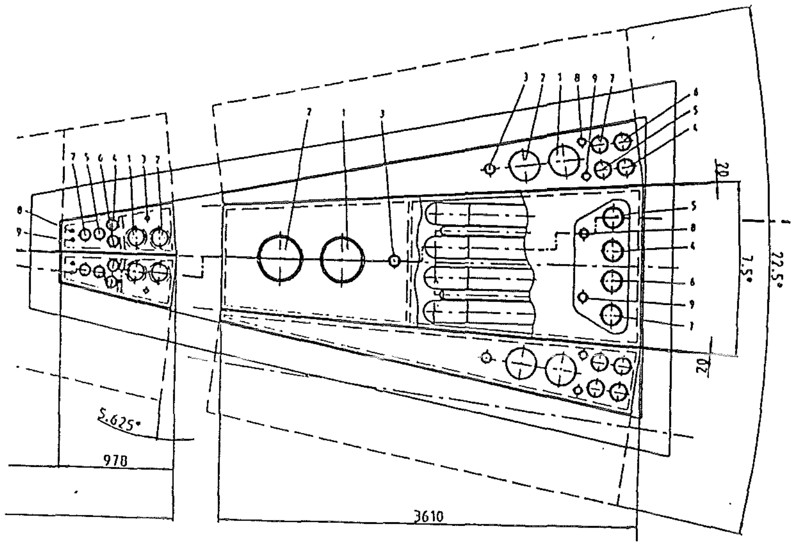


Fig. 1.3 Inlet and outlet tubes (central blanket segment) (from /1.1/)



1 liquid metal inlet
2 liquid metal outlet
3 liquid metal filling/draining
4 helium I inlet
5 helium I outlet
6 helium II inlet

Fig. 1.4 Top view of the flange covering blanket exchange port (from /1.1/)

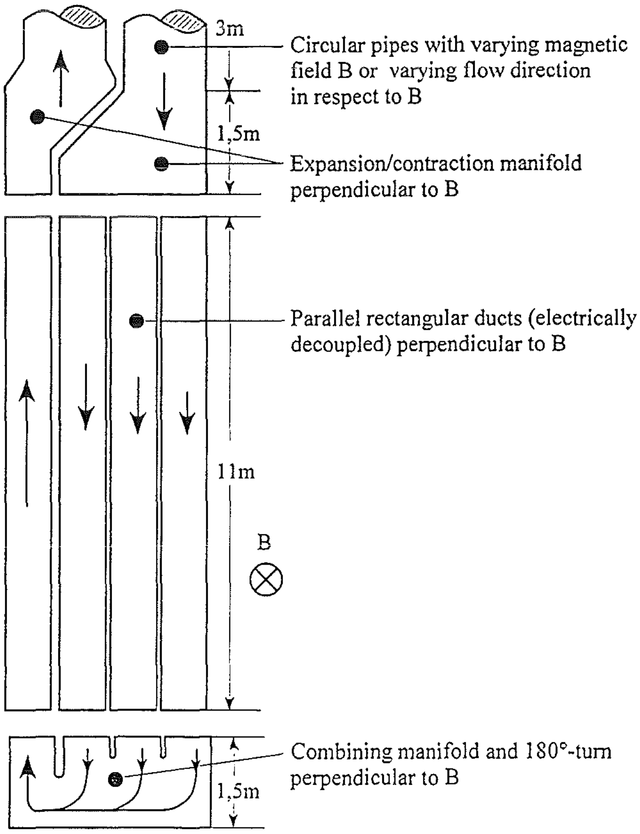


Fig. 1.5 MHD issues of the DCB (from /1.1/)

At the blanket bottom the flow from 3 radially arranged poloidal ducts is combined, turned by 180° and flows upwards in one parallel "front" duct. The flows from 3 parallel front ducts are collected by an outlet manifold which is connected to the outlet pipe. A comprehensive presentation of the MHD-issues is shown in Fig. 1. 5.

A characteristic feature of the DCB is the helium cooling of the first wall region. About 75% of the total heat production is transported by the LM to the external steam generators; this heat is generated essentially by volume heating (which has the important consequence that heat removal from walls is of negligible importance compared to entirely self-cooled blankets).

The liquid metal flow requires some kind of electrical insulation. The reference design is based on the use of a direct coating (dc) of an insulator material (presently, Al_2O_3 is favoured) which results in electrically insulated duct walls (iw). This Al_2O_3 layer is produced by pumping liquid aluminium through the blanket and the subsequent oxidation of the intermediate layer, see /1.1, 1.2/. As back-up solution the use of flow channel inserts (FCI) is foreseen with a metal sheet thickness of 0.5 mm in contact with the LM, resulting in electrically thin conducting walls (cw) /1.5/. The MHD issues are assessed for both types of insulations.

Water Cooled Blanket (WCB)

Again, the description is given for the outboard blanket (Figs. 1.6-1.9, from /1.2, 1.3/). Here, the LM is only circulated for tritium removal, (the circulation of 10 blanket LM inventories per day results in a mean velocity of about 2 mm/s in the blanket box).The LM enters and leaves the blanket box by flowing in the annular gap of concentric circular pipes connected to the top of the blanket box, flows in the gap of the doubled-walled housing of the blanket top and through ducts in the area of the tube plates. Within the blanket, the LM flows downward in the three rear radial rows, turned around at the blanket bottom and flows upward in the two front rows. Appropriate openings in the grid plates have to be provided in order to ensure a homogeneous flow in the ducts. The MHD issues are summarized in Fig. 1.10.

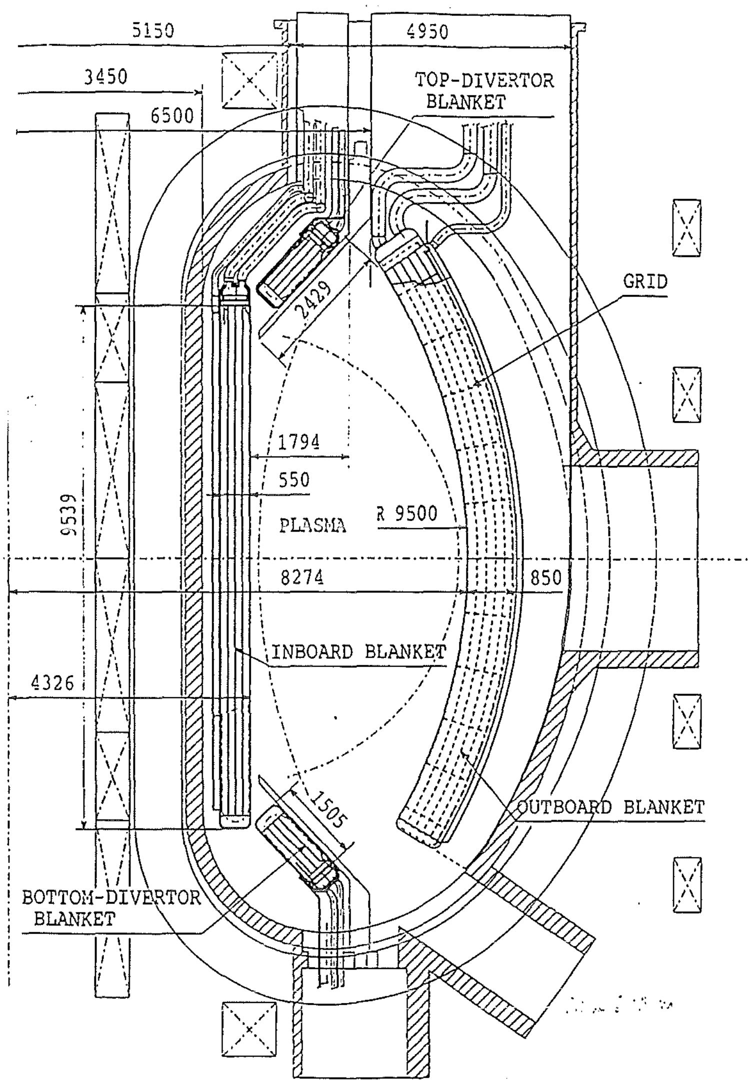


Fig. 1.6 Vertical cross-section of the breeding blanket segments of the WCB (from /1.3/)

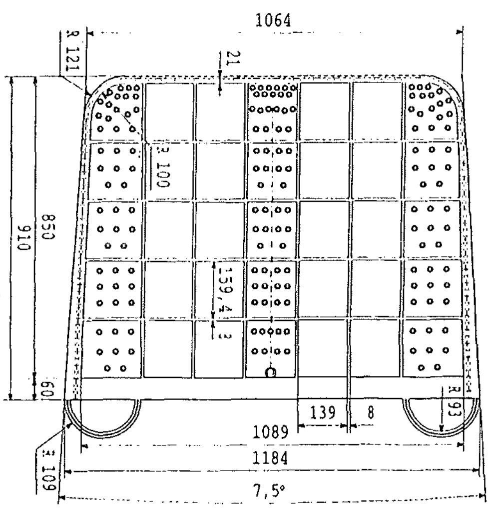


Fig. 1.7 Cross-section of outboard WCB (from /1.3/)

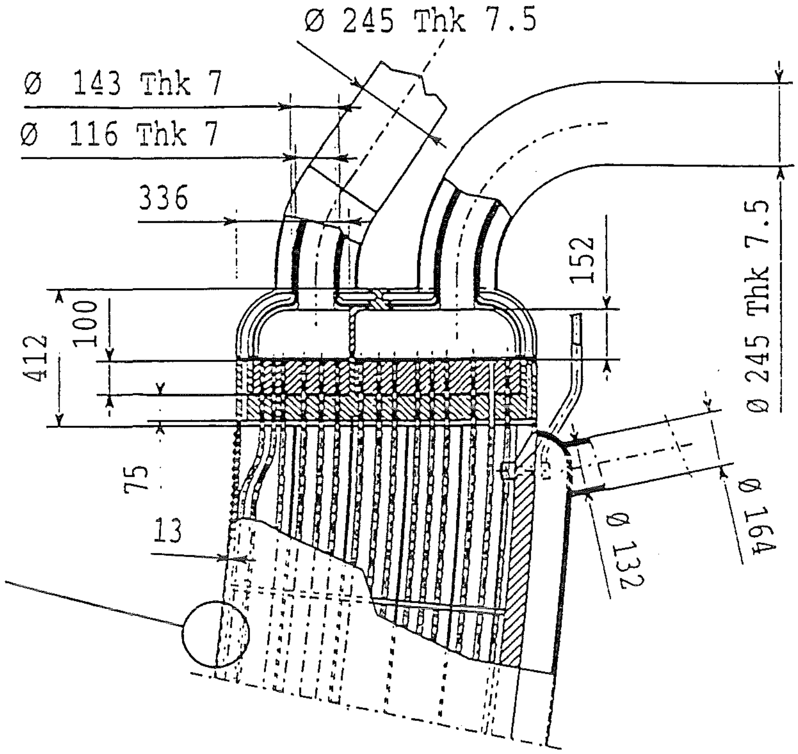


Fig. 1.8 Cross-section of the top header (from /1.3/)

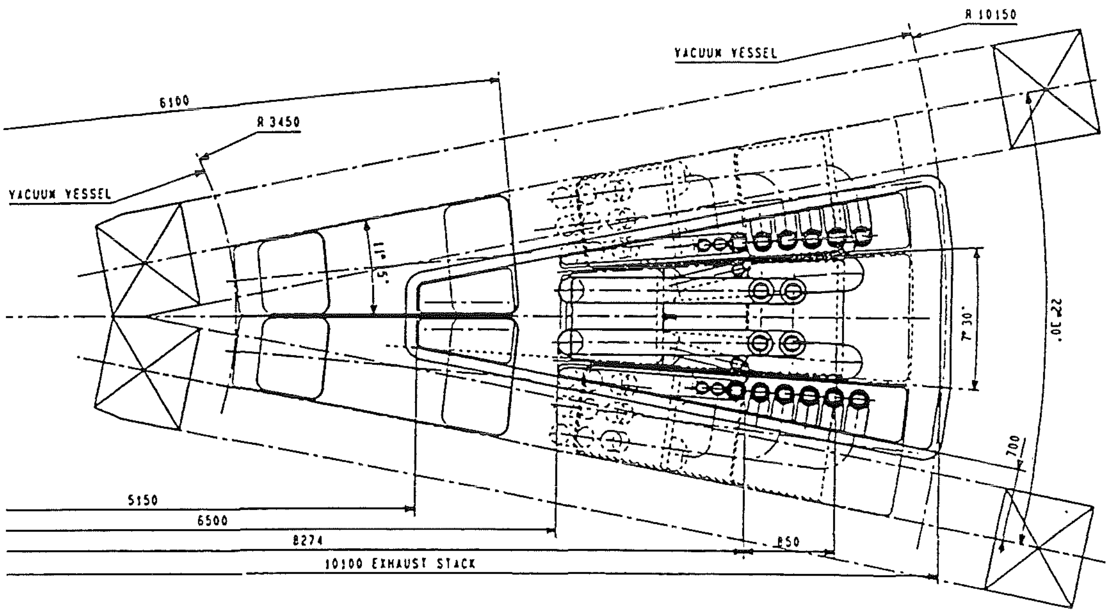


Fig. 1.9 Top view of the flange-covering blanket exchange port for the WCB (from /1.3/)

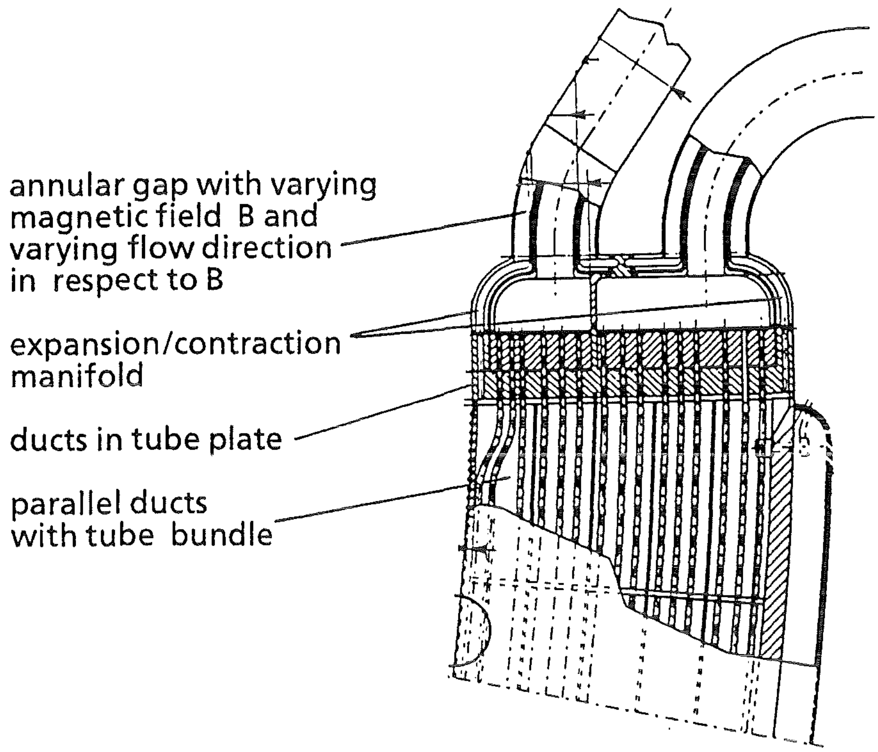


Fig. 1.10 MHD issues of the WCB

In order to reduce tritium permeation losses to the water, the WCB requires permeation barriers on the outside or inside surface of the water tubes. Again a coating of Al_2O_3 is presently favoured.

For the reference design it is assumed that this coating is on the MANET surface facing to the PbLi. If this coating is fabricated in the way as described above, then all internal surfaces facing to the Pb-17Li are covered with an insulating layer (including the grids, the metal plates forming the grid structure within the blanket box and the duct walls in the header and inlet outlet tubes). If the Al_2O_3 layer is produced on the water tubes before installing these tubes in the blanket box then only these surfaces are electrically insulated. Presently the latter method is preferred /1.3/. As back-up solution, the use of permeation barriers on the water side is also considered, which corresponds to LM flow in ducts with thick conducting walls (cw).

1.3 Some Comments on Electrical Insulators

For MHD reasons the feasibility of the DCB is closely connected with the behaviour of the electrical insulator, subjected to thermal stresses, irradiation etc. For the WCB the behaviour of the direct coating, is of high concern for tritium control. This issue is not discussed in the following.

The technology of manufactoring of the two types of insulators is described elsewhere /1.1, 1.2/; technological issues of insulators are discussed in detail in Working Group 8. Due to the interconnection of these areas some comments are made:

- The "radiation induced electrical degradation" (RIED) effect /1.6/ might differ for the dc and the FCI because of
  i) different thicknesses of the insulating layer (dc = 10 μm, FCI = 100 μm). The larger thickness of the FCI insulation is more favourable in respect to irradiation degradation because the potential gradient in the insulation is smaller /1.6/.
  ii) different impurities in the Al_2O_3 due to different manufactoring technologies. It showed that less pure Wesgo-alumina behaved much better than pure Vitex-alumina /1.7/.

Significant differences between dc and FCI might also exist in respect to other degradation mechanisms:

i) due to the mechanical decoupling of the FCI from the thick load carrying structural material the generation of cracks should be smaller
ii) the generation of cracks in the insulation within the sandwiching structure of the FCI does not automatically imply a deterioration of the electrical resistance because there is no direct contact with LM.

2. MHD EFFECTS ON PRESSURE DROP

The flow of an electrically conducting fluid under the influence of a strong magnetic field is characterized by the Hartmann number $M = LB_o(\sigma/\rho v)^{0.5}$, the interaction parameter $N = \sigma L B_o^2/\rho v_o$, the conductivity of the channel wall given by the wall conductance ratio $c = \sigma_w d/\sigma L$ and by the contact resistance at the fluid wall interface denoted dimensionless by $\kappa = (\rho_i \delta_i)\sigma/L$ which can be provided by insulating coatings or by non-perfect wetting. Here L and v_o are characteristic scales of length and velocity in a cross section, B_o is the induction of the applied strong magnetic field. The fluid properties are the density ρ, kinematic viscosity v, and electrical conductivity σ. The conductivity of the wall and its thickness are σ_w and d. The product $\rho_i \cdot \delta_i$ represents the contact resistance at the fluid wall interface. It may be determined by the thickness δ_i and by the resistivity ρ_i of an insulating coating at the duct wall.

In Sections 2.1-2.5 pressure drop issues for conducting walls or perfectly insulating walls are discussed. In Section 2.6 the influence of insulator degradation on pressure drop is considered. Details of duct dimensions, velocities and dimensionless MHD parameters are given in the Tables 2.1 and 2.2.

2.1 Straight ducts

Straight ducts with considerable lengths are essential elements in both blankets (poloidal ducts see Figs. 1.3 and 1.6). For the WCB, the ducts in the tube plates are also of this type. In general flow in straight ducts is well characterized and can be estimated with relative confidence (± 10 %). Below the different types of flows in straight ducts are described and assessments on the magnitude of the resulting pressure drops are made.

Fully developed flow in circular and rectangular ducts: Theoretical results for pressure drop and velocity distribution are summarized in Table 2.3 (from /2.1/). The case $\kappa \rightarrow \infty$ is relevant for perfectly insulating walls (iw) the other, $\kappa \rightarrow 0$, for perfect contact between the fluid and the thin conducting walls (tcw). However, the latter results can be also used to estimate the pressure drop for highly conducting walls (cw)). The validity of these relations for blanket relevant parameters has been verified in many experiments, for details see /2.1, 2.2/.

Influence of developing flow: The influence of entrance lengths on the total MHD pressure drop was assessed to be negligible for the present duct geometries (only for circular pipes with iw, entrance lengths have a larger influence). Therefore, relationships valid for full developed flow are well suited for pressure drop assessments for the given ducts. The values obtained for the two blanket types are listed in Tables 2.1 and 2.2.

Arbitrary cross sections: corresponding results for arbitrary cross sections are obtained by numerical calculations using the Core Flow Approximation /2.3/. An example for this is the calculation of pressure drop and velocity field in the poloidal ducts of the WCB containing the bundle of coolant tubes, compare also Section 3.2.

Section	Geometry	a [m]	L [m]	T [°K]	v [m/s]	B [Tesla]	M [/ *10^4]	N [/ *10^2]	c_{FCI}	Δp_{FCI} [MPa]	$\Delta p_{Insulated}$ [MPa]
1. Inlet (I) and Outlet (O)	circular	0.138	0.84	275 (I)	0.72	0.5-4.5	1.1-1.4	3.0-3.2		0.05 (I)	0.052 (I)
in the fringing magnetic field				425 (O)	0.74				0.0058	0.06 (O)	0.06 (O)
2. Inlet pipe with bends*1	circular	0.138	2.2	275 (I)	0.72	4.5	1.1-1.4	3.0-3.3		0.234 (I)	0.203 (I)
Outlet pipe with bends*1				425 (O)	0.74				0.0058	0.273 (O)	0.200 (O)
3. Inlet and Outlet manifold	change of	0.138	0.6	275 (I)	0.72	5.0	1.4-0.73	3.0-3.3	0.0058-	0.052	0.052
Expansion and Distribution	geometry	-0.066		425 (O)	0.337				0.0114	0.060	0.060
in the subchannels											
4. Poloidal channels*2	rectangle	0.066	11.0			5.0					
Rear				315	0.337		0.65	4.06	0.0118	0.72	0.012
Front				385	1.020		0.73	1.33	0.0114	2.04	0.030
5. Manifold and 180° U-turn	rectangle	0.068	0.6	350	0.337-	5.0	0.69	1.33-4.06	0.0118	0*3	0*3
					1.020		0.71				
6. FCI-overlapping	rectangle	0.066	11.0	350		5.0					
Rear					0.337		0.69	4.04	0.0118	0.163	0
Front					1.020			1.34	0.0114	0.407	
TOTAL OUTBOARD								Δp_{Total}		4.11	0.67

*1 lateral segments

*2 fully developed poloidal flow

*3 included in 4.

Table 2.1 Flow Parameters and Pressure Drops for the DCB

Section	Geometry	a [m]	L [m]	v [m/s]	B [T]	Ha [$Ba\,(\sigma/\rho v)^{1/2}$]	N [$\sigma B^2 a/\rho v$]	Δp [MPa]
1. Inlet (I) and outlet (O) in the fringing magnetic field	annular	0.032 (gap)	4	0.025	from 0.5 to 4	from 500 to 3840	from 33 to 2000	0.28 **
2. Expansion and contraction manifold	3d	0.032	0.4	from 0.025 to 0.05	4	3840	2.10[illegible]	*
3. Ducts of the tubular plate	ellipsoidal	0.015 × 0.04	0.175	0.05	4	240	< 1400	*
4. Parallel ducts	rectangle with internal water tubes	0.15 (max) 0.003 (min)	10	0.002 (I) 0.004 (O)	4	from 120 to 240	<2800	0.02
5. U bends	rectangle	0.91 (max) 0.2 (min)	1	0.003	4	240	< 1400	*
TOTAL (Δp outboard)								0.3

Table 2.2 Flow parameters and pressure drops for the WCB (outboard segment)
(**) : Δp estimated without any 3d-effect and with B uniform (4 T)
(*) : Δp unestimated (assumed unsignificant)

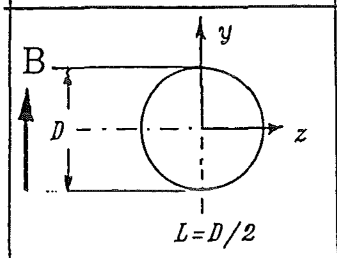
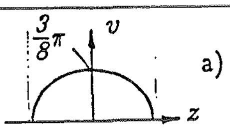
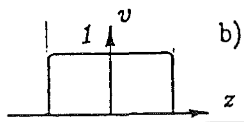
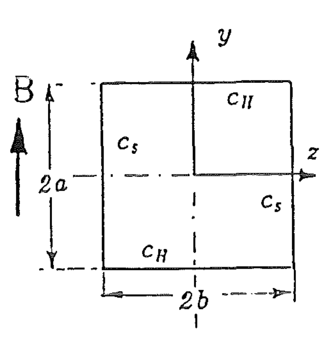
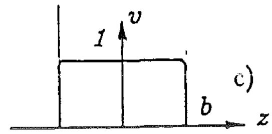
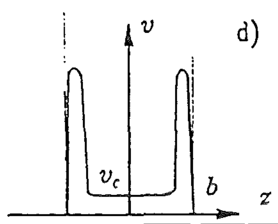
Geometry		∇p	v	
 $L=D/2$	$\kappa=\infty$ insulating	$\frac{3\pi}{8M}$	$\frac{3}{8}\pi \cdot \sqrt{1-z^2}$	
	$\kappa=0$ conducting	$\frac{c}{1+c}$, $c \gg M^{-1}$	1	
 $L=a$	$\kappa=\infty$ insulating	$\frac{1}{M}$	1	
	$\kappa=0$ conducting	$\frac{\partial_x p_H}{1+\frac{a\partial_x p_H}{3bc_s'}}$ where $\partial_x p_H=\frac{c_H+M^{-1}}{c_H+1}$, $c_s'=c_s+M^{-\frac{1}{2}}$	$v_c=\frac{\nabla p}{\partial_x p_H}$	

Table 2.3 Pressure drop correlations for fully developed MHD duct flow (from /2.1/)

Influence of nonalignment of magnetic field: Due to the curvature of the toroidal magnetic field and the plane walls in the blanket box, the magnetic field is not perfectly aligned with the side walls of the rectangular poloidal ducts Figure 2.1 from /2.4/ shows that this effect of nonalignment on pressure drop is negligible for the small angles β of occuring in the blanket.

Influence of changing magnetic field in flow direction: the previous assessments were based on the assumption of a constant magnetic field B in the toroidal direction. In the blanket torus, however, a vertical field component (about 10 % of the toroidal field) is required. In the blanket midplane this component is parallel to flow direction in the poloidal ducts and does not contribute there to pressure drop. Due to the curvature of the blanket in poloidal direction this vertical field component in general results in a component perpendicular to the flow; this component increases with increasing distance from the midplane. The superposition of this component with the toroidal field results also in a similar nonalignment as discussed above. Maximum inclination angles at the blanket ends are a few degrees. The influence of this effect including the variation of this angle in flow direction is assessed to be small.

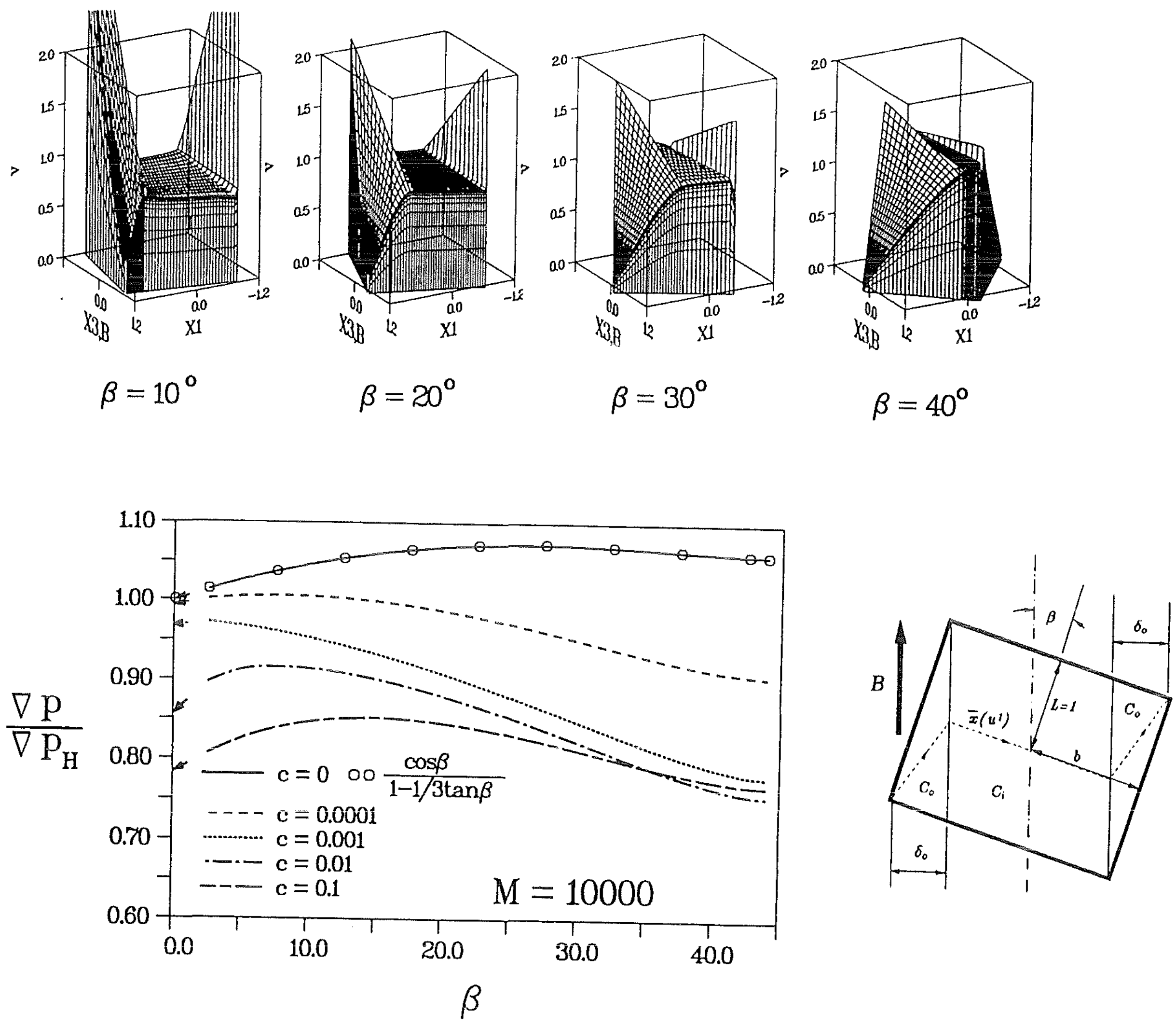


Fig. 2.1 MHD flow in inclined rectangular ducts (from /2.4/)

The evaluated pressure drops for flows in straight ducts are given in the Tables 2.1 and 2.2. For the DCB the flow in the poloidal ducts results for dc in a very small value of about 0.04 MPa and for FCIs in a value of about 2.7 MPa. The latter value could be considerably reduced by design measures if this blanket option would be developed in more detail, see Section 2.6. For the WCB it was assumed that all surfaces in contact with Pb-17Li are either perfectly insulated or not insulated. The pressure drop becomes negligible for both versions.

2.2 Overlapping of FCIs

For the DCB with FCIs it was assumed that the FCIs are manufactured with lengths of 1 m and are installed in the duct with an overlapping of 6 cm at both ends. This overlapping zone represents a small flow expansion. Three dimensional electric currents can flow inside the LM-filled gap and enter the highly conducting duct walls. A theoretical analyses /2.5/ predicts for the present assumptions a pressure drop of about 0.56 MPa.

2.3 Circular pipes with varying magnetic field B and/or varying flow direction in respect to B.

The DCB uses circular inlet and outlet pipes with bends which result in flow directions partly aligned with the magnetic field. Such bends cause additional pressure drops due to three-dimensional (3d) currents. These pipes also penetrate the magnetic field which results in additional pressure drops due to 3d currents.

The MHD flow in fringing fields was first investigated in detail by /2.6/ for thin conducting walls (and later verified in several experiments). The relationships are summarized in Table 2.4. The corresponding relationships for dc (corresponding to C=0) are also listed. Table 2.1 shows that the additional pressure drops are small.

In order to predict the pressure drop in the bends partly aligned with the magnetic field, relationships were used from detailed theoretical and experimental investigations in a rectangular, thin walled duct /2.7/. The relationship (see Table 2.3) consists of the term Δp_{asympt}, valid for intertialess flow and an empirical expression which is a function of the Interaction parameter and Hartmann number describing inertial effects. The use of this term for the circular pipe in the blanket is believed to result in a conservative pressure drop assessment due to two reasons

i) the occurance of strong side layers which favour 3d currents are smaller for circular pipes
ii) 3d effects are significantly reduced if sharp-edged changes of cross-sections in magnetic field direction (as investigated experimentally) are avoided.

Table 2.4 Pressure Drop Correlations for Complex Duct Geometries

Normalized quantities used:

$$\Delta p^* = \Delta p / (L^* a \sigma u B^2)$$

$$(\Delta p / \Delta x)^* = (\Delta p / \Delta x) / (\sigma u B^2)$$

Circular pipe with dB/dx ≠ 0 /2.6/:

$$\Delta p^* = \Delta p^*_{fd} + \Delta p^*_{3D}$$

$C > 0$ | $C = 0$

$$\Delta p^*_{fd} = \frac{C}{1+C};\ L^* = L / a \quad \Big| \quad \Delta p^*_{fd} = \frac{3\pi}{8}\frac{1}{M}\ L^* = L / a$$

$$\Delta p^*_{3D} = 0.006;\ L^* = 1$$

Circular pipe with bend in direction of B /2.7/:

$$\Delta p^* = \Delta p^*_{asymp} + 0.24 \cdot N^{-0.23}\ [1 + 1.01\ M^{-1/2}]$$

$$\Delta p^*_{asymp} = \Delta p^*_{fd} + \Delta p^*_{3D}$$

$C > 0$ | $C = 0$

$$\Delta p^*_{fd} = C / (1+C);\ L^* = L / a \quad \Big| \quad \Delta p^*_{fd} = \pi / (8M);\ L^* = L / a$$

$$\Delta p^*_{3D} = 0.563 \cdot \Delta p^*_{fd};\ L^* = 1$$

Expansion/contraction manifold /2.5/:

$C > 0:\ \Delta p^*_{3D} = 0.6;\ L^* = 1$ | $C = 0$: *assumed*: $\Delta p^*_{3D} = 0.6;\ L^* = 1$

Combining manifold and 180°-turn (2d duct) /2.10/:

$$\Delta p^* = \Delta p^*_{fd}$$

Δp^*_{fd} with relationships for rectangular duct flow (length of flow path equal to lengths of corresponding duct axis

For FCIs about 20 % of the total blanket pressure drop is calculated for the inlet and outlet pipes of the lateral blanket segments, see Fig. 1.3; the major part origines from the term representing inertia effects.

For iw it was assumed that the term representing the influence of inertia is also valid for this case. The fact that pressure drops due to 3d currents are very similar for ducts with tcw and iw was experimentally verified in other experiments /2.8/.Then this term dominates even more the pressure drop in the inlet and outlet pipes and results in the major contribution (about 60 %) of the total blanket pressure drop. However, again one should keep in mind that this pressure drop assessment is very conservative.

For the annular pipes of the WCB the pressure losses were assessed assuming that the magnetic field is everywhere perpendicular to the pipe axis and uniform (4T) and neglecting the pipe curvature. This estimation, which neglects the contribution of the 3d currents, may be considered as conservative because it maximizes the predominant contribution of the transverse component of the magnetic field. This is the major part (0.28 MPa) of the total pressure loss, since the velocity in these annular pipes (25 mm/s) is significantly larger than in the straight ducts (2 to 4 mm/s) In these ducts the pressure loss has been calculated assuming the wall electrically conducting (cw); it should be still smaller for iw. It is worth to notice that the velocity distribution through the annular jet issuing from this pipe might be strongly non-uniform, and that detailed studies should be performed to insure an almost uniform feeding of the straight tubes of both the inboard and outboard segments.

2.4 Inlet and outlet manifolds

The inlet and outlet manifolds consist of expanding or contracting ducts connected with a circular tube and an array of parallel rectangular ducts (where for the inlet manifold a special flow rate distribution is required).

Expansion/contractions give rise to additional pressure drops due to 3d currents if the change of cross section occurs in the direction of the magnetic field. This is the case for both types of manifolds.

From the first detailed theoretical investigations (valid for inertia less MHD flow) for such manifold with tcw it was concluded (2.9):

"The results indicate that pressure drop associated with manifolds is only a small fraction of the overall pressure drop, and that desirable flow distribution among coolant ducts can be achieved with a judicious choice of wall thickness distribution. As a result the MHD effects related to manifolds of this type can be neglected during the blanket conceptual design phase".

Results from similar theoretical assessments for the present expanding inlet geometry /2.4/ are shown in Fig. 2.2: Again the additional pressure drop is very small (comparable to the pressure drop for fully developed flow over one characteristic length).

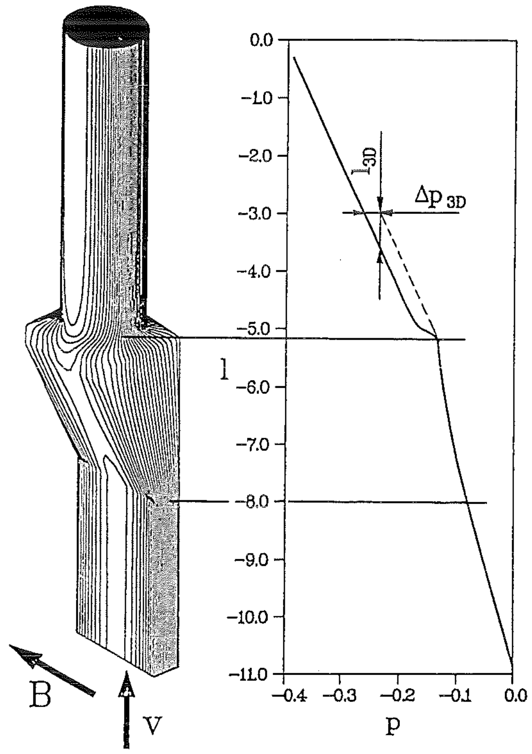


Fig. 2.2 3d MHD flow in the expansion of the outlet manifold (M = 1000, C = 0.05) (from /2.4/)

The influence of inertial effects for blanket relevant values of N and M was taken into account by a factor of two. Table 2.2 shows that the absolute values of the pressure drop are moderate. Again it has to be mentioned that no detailed knowledge exists in order to assess accurately the inertia effects. However, it is believed that the unaccuracy is not so large that the pressure drop increases significantly.

For iw again the same value was assumed as for tcw. The contribution of this 3d effect pressure drop to the total pressure drop is about 16 %.

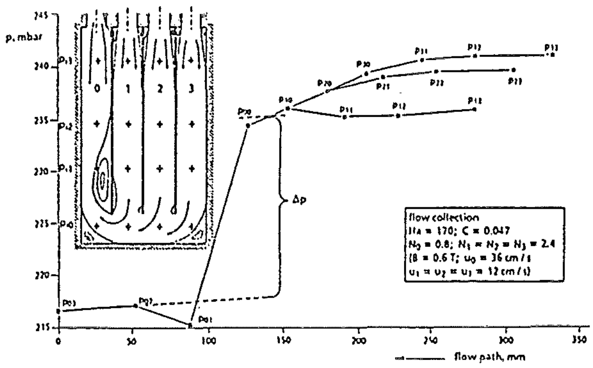
In the inlet manifold of the WCB (see Fig. 1.6) a crude assessment of the pressure loss has been done assuming that the kinetic energy of the fluid coming from the annular pipe is completely lost. This quite conservative assumption leads to a negligible pressure loss. The same conclusion is *a fortiori* valid for the outlet manifold.

2.5 Combining manifold and 180° turn at blanket bottom

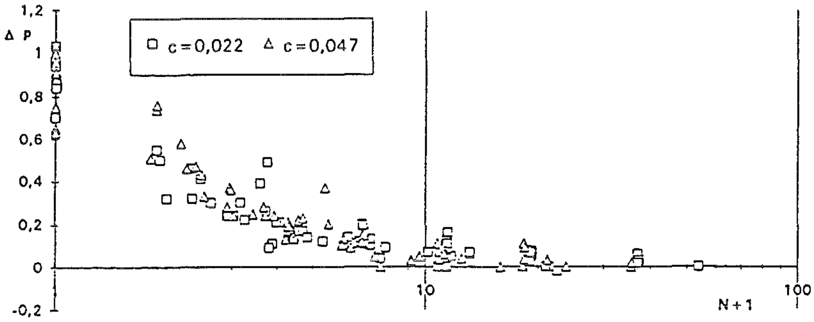
In the DCB the downward flow of 3 radial ducts is combined at the blanket bottom and flows upward in one duct. For this flow geometry there is no change of duct dimensions in direction of the (toroidal) magnetic field, therefore no additional pressure drops due to 3d currents are expected. Figure 2.3a) (from /2.10/) shows that pressure drops due to inertial effects exist at very low values of the Interaction parameter; Fig. 2.3b), however, depicts that these pressure drops vanish already at values of N far below values of interest in the blanket. Therefore, the MHD pressure drop can be evaluated with sufficient accuracy by assuming fully developed flow in the parts of the individual ducts.

2.6 DCB optimized for the use of FCIs

The duct geometries of the DCB discussed in the previous sections were optimized for the use of direct coatings. If these ducts are equipped with FCIs a total pressure drop of $\approx$ 4.3 MPa is assessed. This value still results in a large safety margin in regard to the tolerable internal pressure. However, there are several design measures to decrease significantly the pressure drop if this blanket option would be developed in more detail as shown in Table 2.5. An estimation of the total pressure drop of the DCB optimized for FCIs leads to $\approx$ 3 MPa.



Pressure distribution in the blanket relevant geometry
($N_o = 0.8, N=N_1=N_2=N_3=2.4, Ha=170, C=0.047$)



Loss coefficient for duct "0" of the blanket relevant geometry
($0<Ha<360, C=0.02; 0.047$, different flow ratios in ducts 1,2 and 3)

Fig. 2.3 Pressure distribution and 3d loss coefficient for blanket bottom geometry of the DCB (from /2.10/)

individual measure	$\Delta p_{red} / \Delta p_{total}$ (%)
reduction of thickness of inner FCI steel sheets from 0.5 to 0.3 mm	35
increase of radial duct dimension of front channel by a factor of 2	20
increase of toroidal front duct dimension by decreasing the number of radial grid plates from 4 to 3	13
increase of FCI length from 1 m to 3 m	9

Table 2.5 DCB with FCIs: Measures to reduce pressure drop

2.7 Imperfect electrical insulations

2.7.1 Degradation of direct insulating coatings

Homogeneous degradation: A homogeneous degradation might occur due to irradiation or homogeneously distributed small cracks. This degradation can be expressed by the dimensionless resistance $\kappa = \rho_i \delta_i \sigma/a$. The value $\kappa \rightarrow \infty$ refers to the case of perfect insulation. For an insulator thickness of $\delta_i = 10\ \mu m$ and a specific resistance for unirradiated Al_2O_3 of $\rho_i = 10^9 \Omega m$ and characteristic values for the poloidal duct of the DCB ($a = 0.066$ m, $\sigma = 0.7 \cdot 10^6 A/(Vm)$) the resistance κ becomes $\kappa \approx 10^{11}$. Figure 2.4 (from /2.11/) shows that κ can decrease several orders of magnitudes without significantly influencing the pressure drop.

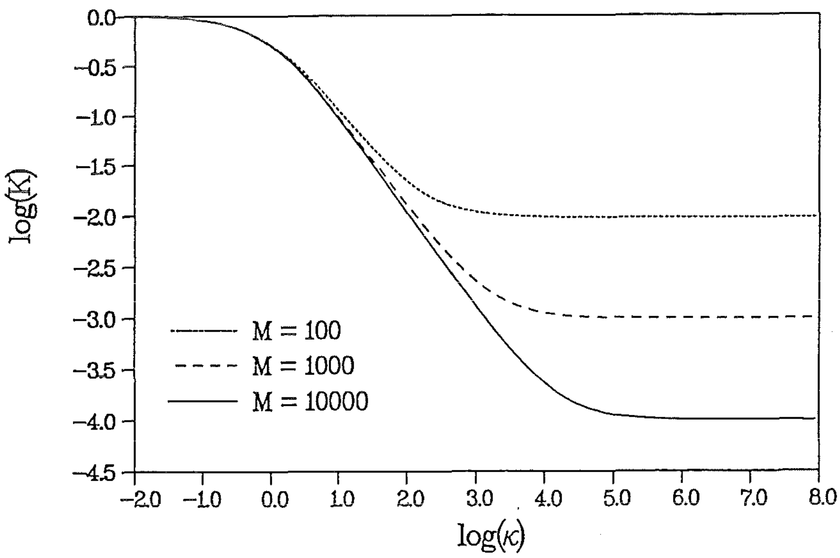


Fig. 2.4 Pressure drop in rectangular ducts as a function of the resistance of the insulating coating (from /2.11/)

Due to the small values of the pressure drop in ducts with perfectly insulating coatings a significant pressure drop increase could be accepted in respect to pumping power considerations. However, it cannot be ensured that in parallel ducts (connected to common manifolds at both ends) this degradation is equal in each duct. Unequal pressure drops would cause unequal flow rates which are not acceptable for heat removal. Therefore, in the following only a pressure drop increase of 10 % is accepted. Based on simplifying considerations /2.12/ the resistance κ is given by

$$\kappa = M/\alpha \tag{1}$$

where α corresponds to the ratio of pressure drop increase to pressure drop for perfect insulation. For M = 10 000, a value of κ = 10^5 is obtained which is 6 orders of magnitudes smaller than the value for undegradated material.

<u>Partly damaged direct coatings:</u> Direct coatings are connected with the load carrying walls. Different expansion coefficients, low tensile strength and ductility can give rise to generation of cracks or "bad" spots due to flaking during thermal cycles. Thermal cycles are caused by changing operational conditions; another reason might be low-frequent turbulence fluctuations within the LM. If the LM penetrates in these cracks respectively wets perfectly the bad spots, significant increases of MHD pressure drop (and changes of velocity profiles) can occur. The amount of generation of imperfections, the wetting mechanism and the healing mechanisms are poorly understood. Therefore, only very rough assumption can be made in order to assess the influence of the degradation on pressure drop. In the following it is assumed that always perfect wetting occurs.

Damages have the most adverse effect if they exist at opposing sides of a duct; damages in one side wall of a rectangular duct would have not influence at all. Figure 2.5 (from /2.13/) shows the influence of two opposing line cracks (extending over the total duct lengths) on the pressure drop in a circular pipe as a function of the resistance r which is in a first approximation proportional to the nondimensional contact resistance κ.

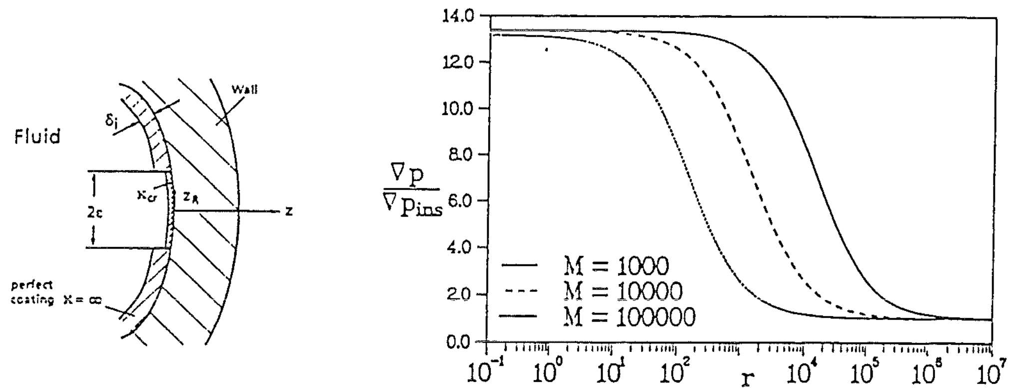


Fig. 2.5 Pressure drop in a circular pipe with two line cracks at both sides as a function of the resistance r (from /2.14/)

For very low values of r, relevant for an almost perfect electrical contact between LM and wall, the pressure drop increases by more than one order of magnitude (independent of the crack width ε as long as ε< < pipe diameter). Such a pressure drop is not acceptable for blanket operation as mentioned above. Figure 2.6 shows corresponding results for a pair of conducting spots (again R is proportional to κ). For $\kappa \rightarrow 0$, for Δp_{3d} a value is obtained which corresponds to that of a fully developed insulating duct flow over 24 characteristic lengths.

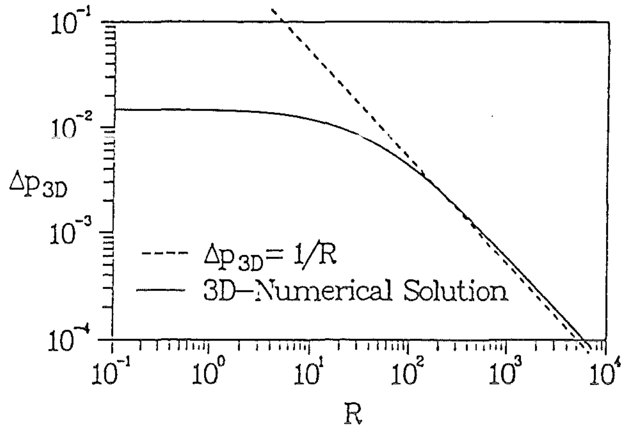


Fig. 2.6 Additive pressure drop of a pair of conducting spots in a circular pipe as a function of the resistance R (M = 1000) (from /2.14/)

Therefore, the requirements for blanket operation can be only met if the contact resistance at the damaged area expressed by the product ρδ, respectively κ, is not too low. For the range where the pressure drop starts to increase with decreasing κ the following simplified relationship was deduced /2.12/ for rectangular ducts:

$$\kappa = fM/\alpha \qquad (2)$$

where f is the ratio of damaged coating surface to the total side wall surface. Relationship (2) is valid both for finite small crack and "bad" spots. For a pressure increase of 10 % and a damaged surface fraction of 1 % the contact resistance can be two orders of magnitudes smaller than for homogeneous insulator degradation which means seven orders of magnitudes smaller than for undamaged insulation.

This shows that the influence of partial damages is essentially smaller if the insulator behaviour is not perfectly lost during damaging or if the generation of a new insulating coating is fast.

Generation and healing of imperfections: Self-healing of the damaged dc is considered to be mandatory for the use of dc. (For a damaged Al_2O_3 coating the envisaged process is the diffusion of oxygen to the Al-rich sublayer). Fortunately, the insulation requirements for the damaged parts are not high. Insulator thicknesses below the µm-range already contribute significantly to a reduction of pressure drop.

Assuming a parabolic growth rate law, valid for diffusion controlled layer build up the following relationship /2.12/ was proposed for the equilibrium between damage generation and healing:

$$G^* = \frac{G}{A_{sidewall}} = \frac{\rho\, t_H}{4\tau_H} \frac{\alpha}{b} \frac{\sigma}{M} \qquad (3)$$

where τ_H is the time where the damage is healed which occurs when the thickness t_H is reached and G is the maximum tolerable crack generation rate.

Assuming $t_H = 10^{-6}$ m, $\tau_H = 10^6$s ($\approx$12 days), an additional pressure increase of 10 % and values relevant for the poloidal duct of the DCB, a value of $G^* = 3{,}5 \cdot 10^{-7}$ s^{-1} is obtained which means that a damage of about 3% per day of the total side wall surface can be accepted. Again it is emphasized that Eq. (3) is based on very simplifying assumptions and that presently no validated data exist for the values of t_H and τ_H.

Measures to decrease the impact of partly damaged parallel ducts: In the previous assessments only an pressure drop increase of 10 % due to damages in the dc was accepted in order to avoid a significant nonuniform flow distribution. The influence of these pressure increases can be decreased by imposing a large pressure drop at some point in the duct (throttling) or by flow balancing by electrical coupling of the parallel ducts, see /2.14/. If for instance a (physical or MHD) throttle provides 5 times the pressure drop of the perfectly insulated duct, then a 60 % increase in pressure drop will reduce the flow rate only by 10 %. Due to the low pressure drops of perfectly insulated ducts such a measure could be acceptable. Much more favourable results are obtained with the electrical coupling of ducts, see /2.14/.

2.7.2 Degradation of the insulation within FCIs

Some differences in respect to insulator degradation of direct coatings and FCIs were mentioned in Section 1.3.

For MHD reasons the influence of homogeneous degradation is also smaller for FCIs than for dc: electric currents can freely flow within the metal sheet in contact with the LM. If the insulator behind this metal sheet degradates, only a small fraction of the electrical current enters the degradated insulator. Figure 2.7 (from /1.2/) shows that the increase of pressure drop for decreasing κ occurs at a value about 2 orders of magnitudes smaller than for dc (compare Fig. 2.4). Taking into account the larger thickness of the insulating layer in the FCI, the acceptable insulator degradation differs by three orders of magnitude.

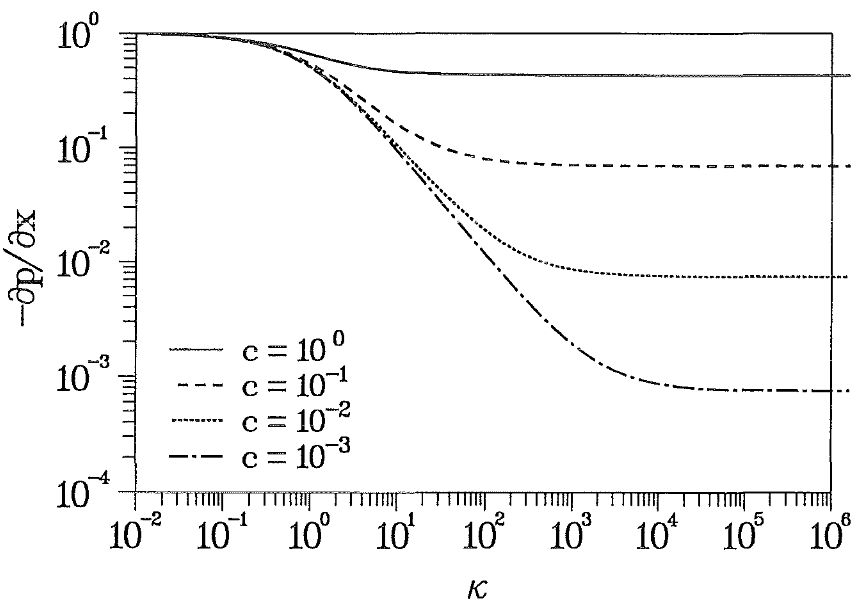


Fig. 2.7 Pressure drop in rectangular ducts equipped with FCIs as a function of the resistance of the insulator (from /2.13/)

The results on the degradation of insulators (dc and FCI) can be summarized as follows:

- For direct insulating coatings the generation of damages is a critical issue for the DCB. The present knowledge does not allow to quantify if such a blanket is feasible

The problem of insulator damages in FCIs might be less severe because:

i) there is no direct contact between LM and insulation

ii) the irradiation degradation might be smaller because of the larger insulator thickness (irradiation effects increase with the electric potential gradient in the insulator)
iii) the tolerable insulator degradation can be larger because the pressure drop is less sensitively dependent in the insulation.

Nevertheless the irradiation effect is still considered as a very important issue and it must be shown that irradiated FCIs behave well under relevant duct flow (vibrations, temperature and pressure fluctuations).

3. MHD EFFECTS ON VELOCITY DISTRIBUTIONS AND THE CONSEQUENCES ON TRANSPORT PHENOMENA

3.1 General remarks

The transfer processes for heat, tritium and corrosion products depend sensitively on the velocity distributions close to the walls. These velocity distributions for blanket-relevant MHD parameters are presently not sufficiently known. Up to now, only the distributions for laminar, inertialess MHD flow have been calculated. These calculations predict for thin conducting walls (tcw) very "unusual" distributions due to thin layers with high velocities close to the walls and free shear layer within the core. As an example, Fig. 2.1 shows how sensitively these velocity distributions depend on small angles of inclination of the magnetic field. For iw, these high-velocity wall layers do not exist.

For blanket-relevant conditions, one should consider that there is a competition between the mechanism of formation of such layers with high-velocity gradients and their natural instability which tends to generate some local two-dimensional turbulence, which results itself in a mixing effect perpendicular to the mean velocity. The available results on this (/3.1/, 3.2/), which have been obtained under moderate magnetic field, should be extended to higher values of the magnetic field in order to ensure reliable predictions.

3.2 Heat transfer

Heat transfer is not of first-order relevance in both concepts since, in each case, there is no need of an efficient convection to remove the heat from the first wall. In the DCB, the first wall and (partially) the second wall are cooled by helium, so that the heat to be removed is generated in the volume of the liquid metal itself and is transported outside by the mean flow without any need of high transfer coefficients. In the WCB, the heat is removed from the blanket by water. Within the liquid metal the assumption has been made that heat is only transported by conduction.

However, two second-order questions seem to merit some basic studies and should be addressed for each concept: what could be the influence of free convection and what could be the influence of turbulence?

3.2.1 Assessment of the role of free convection

Any problem of free convection is characterized by three vectors: the temperature gradient (mainly horizontal and radial in the blanket), gravity (vertical), and magnetic field (mainly horizontal and toroidal, but the poloidal component might become relevant when the influence of the toroidal one becomes very small). It is also clear that the driving torque is proportional to the vector product $g \times \nabla T$, and that this vector product is significant in the blanket segments since both vectors are perpendicular. It is also clear that the MHD braking of this kind of flow /3.4/ is

- maximum when B is within the plane of the flow and perpendicular to the main direction of the velocity (vertical in the blanket),
- intermediate when B is within the plane of the flow and parallel to the main direction of the velocity (as B_P),
- minimum when B is perpendicular to the plane of the flow.

In the blanket, the most typical free convection flow is a plane motion with a very long vertical flow, upwards where the temperature is high and downwards where it is low. The favoured plane is perpendicular to the toroidal magnetic field, since it suffers some damping by this component of the magnetic field only within the Hartmann layers present along the strengthening plates. The influence of the poloidal magnetic field on such a plane flow is limited to the domain where the flow is recirculating (not parallel) and is responsible for an extension of this domain on a typical length of the order of Ha_P (Hartmann number defined with the poloidal field). The vertical velocity which may be deduced from available scaling laws (/3.3/ and /3.4/), which have recently received some experimental validation /3.5/, is of the order of 10 cm/s if the temperature gradient is of the order of 100°K.

These values are considerably higher than the velocities assumed in the design of the WCB (2 to 4 mm/s). Free convection could therefore significantly alter the temperature distribution. The convective upward flow would transport the hot fluid near the outlet and increase there the radial temperature difference. More investigations are required in order to make reliable assessments and to modify the location of the water tubes in order to properly take into account free and forced convection. These investigations are only required for the later detailed blanket design phase.

For the DCB no significant temperature differences exist betweeen walls and the LM. In a laminar flow with constant velocity in the duct a maximum temperature difference of about 50°K due to nonhomogeneous internal heat production occurs at the outlet of the first duct row. Buoyancy effects would enhance the velocity in the zone of high temperatures and, therefore, decrease the maximum temperature, an effect which is beneficial.

3.2.2 Assessment of the role of turbulence

From the available knowledge on MHD turbulence, the clearest point is that only large two-dimensional eddies can persist. As a matter of fact, all the other turbulent modes would be submitted to a very efficient Joule dissipation and could not survive. These large 2d eddies would be like columns aligned with the magnetic field. Their driving mechanism would be the shear, likely to be expected in the DCB where strong velocity gradients exist. Their amplitude would result from an energy balance between this driving mechanism and the Hartmann friction necessarily present at their ends /3.6/. The data now available have not been obtained in the same kind of flows, nor with very high magnetic field. Nevertheless, they confirm that some turbulence persists in the presence of a high magnetic field, with almost the same level as without a magnetic field, but with higher instantaneous amplitudes and with low frequencies. And they suggest that the heat transfer rate from walls may be 2 to 6 times larger than without the turbulence, whereas the pressure loss would not be changed.

For the WCB, one may however conjecture that the turbulence effect should be much less relevant because of its small velocities and Reynolds numbers.

For the DCB this turbulence effect would be beneficial if the frequency of the 2d eddies is not too low. Then, these eddies homogenize the radial mean temperature profile caused by the nonhomogeneous heat production. If these frequencies are very low (eg $<<$ 1 Hz), there is the concern that large eddies transport colder LM from the rear to the front. The question is if eddies could generate cracks in the coatings. Blanket-relevant experiments are required especially taking into account the poloidal component of the magnetic field. This component is small compared to the toroidal magnetic field, however, the damping effect might be sufficient to prevent the formation of large-scale turbulence.

3.3 Tritium transport

The main risk is that some kind of quasi-steady trapped eddies exist, and that the tritium generated within the core of these eddies reaches large values, only limited by diffusion. Such eddies are usually referred to as "stagnant zones". Two kinds of mechanisms may be imagined to generate such stagnant zones, as detailed below, one is due to the very specific velocity distributions which may be present, the other is due to free convection.

3.3.1 Influence of velocity distribution

Strange and spectacular velocity distributions are predicted by those who are using the laminar flow approximation /3.7, 3.8/ to model the velocity distribution in all kinds of situations where 3d electric currents are likely to be present. Their main characters are: i) the presence of very large velocities in jet-like boundary layers, ii) the corresponding very low core velocity, and iii) the asymmetries due to the 3d electric circuit. Nobody can now exclude that, in some circumstances where j would have a particular direction, the j x B force might locally drive some secondary flow in the direction opposed to the driving pressure gradient. This suggests that, in both cases (DCB and WCB), stagnant zones may exist. And it cannot be argued that this effect is more plausible in one concept than in the other, because, the current density being almost proportional to the velocity, it is as easy to oppose a mean velocity of the order of 30 cm/s as to oppose a velocity of the order of 2 mm/s. Indeed, this risk should be considered as a property of the duct design, independently of the value of the mean velocity. It is important to quote that such an effect, essentially related to the design, might be easily prevented with an appropriate design, to be specifically adjusted during the next stage of the detailed design phase.

3.3.2 Influence of free convection

From the assessment made in Section 3.2.1, it seems clear that there are possibilities for the velocities driven by free convection to be larger than that of the mean flow in the WCB. But, again, this appears to be, essentially, a matter of design. So, it is recommended to pay a particular attention to this question in the detailed design phase.

3.4 Corrosion and mass transport

3.4.1 Compatibility of Al_2O_3

Al_2O_3 has an excellent compatibility with Pb-17Li as demonstrated in experiments at 450°C where no material losses were observed after 1000 hours operational time /3.9/. In industrial applications, Al_2O_3 layers are purposely used to protect steels against corrosion.

Although no experiments with magnetic fields exist it is supposed that corrosion in the blanket is of no concern as long as Al_2O_3 layers are used.

3.4.2 Corrosion of MANET

For corrosion of MANET in contact with Pb-17Li a diffusion-governed corrosion mechanism was observed in experiments without magnetic field /3.10/. A correlation characteristic for turbulent flow was found

$$\dot{m}_{corr} = 8 \cdot 10^{9} \cdot d^{-.125} \, e^{-25690/(1.987T)} \qquad (4)$$

where d is the pipe diameter, v is the mean velocity, T the temperature (in K) and $\dot{m}_{corr}$ is the corrosion mass flow rate (in µm $year^{-1}$).

For diffusion-governed corrosion, velocity gradients at the wall and the type of flow (laminar or turbulent) play the important role. For LM flow in magnetic fields the mass transfer mechanism is not sufficiently known. Calculations based on inertialess laminar flow result in very strong velocity gradients (and strange velocity profiles) as discussed earlier, see Fig. 2.1. Assessments for the conservative case of a constant velocity in the channel up to the wall (slug flow), however, demonstrate that the corrosion rate after a small entrance length becomes smaller than for turbulent flow without magnetic field, see Fig. 3.1 from (/3.11/).

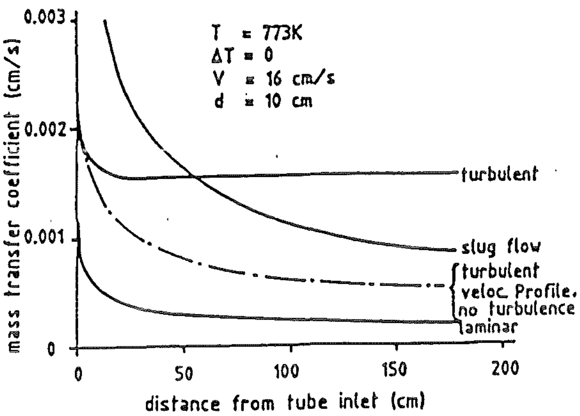


Fig. 3.1 Influence of velocity profile and flow regime on mass transfer coefficient (from /3.11/)

If MHD turbulence is of importance, corrosion rates might increase considerably. (However, MHD turbulence is expected to be much less expressed for electrically conducting walls due to the braking effect.) Up to now, the influence of the magnetic field was investigated in two types of experiments: In the first one free convection flow in a box existed /3.12/. Here, the magnetic field increased the corrosion rates by about 30 % for martensitic steel (and about 50 % for austenitic steel). These experiments cannot be used for extrapolation due to the poorly known temperature and velocity distributions.

Results from experiments with forced convection duct flow did not show an increased corrosion rate due to MHD effects /3.13/. However, an austenitic steel was used which again does not allow to extrapolate these results for blanket conditions.

High corrosion rates may thin unacceptably the structures and may lead to undesired deposition effects, see Section 3.4.2. The first effect might influence the DCB with FCIs (the effect might be of less importance for the WCB). However, the corresponding steel sheet thickness could be increased in the area of high interface temperatures without increasing considerably the total blanket pressure drop.

3.4.3 Deposition of corrosion products

The deposition of corrosion products may lead to flow restrictions which decrease the flow rate (for constant pumping power) which deteriorates heat transport (of importance for the DCB) or tritium transport (relevant for the WCB). Furthermore, the uncontrolled deposition of radioactive corrosion products in the LM loop can generate problems of maintenance and shielding.

Of special interest is the influence of the magnetic field on corrosion product deposition because the blanket itself might act as a huge magnetic trap. However, it should be recalled that the deposition mechanism in magnetic traps is based on the magnetic susceptibility of suspended particles and significant magnetic field gradients. Therefore, the piping from the blanket segments to the heat or tritium removal systems are the most endangered.

Presently, there is no general agreement on the deposition mechanism in large MANET-PbLi loop systems. In systems with high corrosion product concentrations (capsule tests or flow systems with no very effective purification systems) a favoured deposition in magnetic traps was observed /1.2/. Reasons for this could be that homogeneous nucleation occured (crystal formation within the LM) or broken off crystals from other parts were trapped. For the proposed purification system of a fusion power reactor /3.14/ it was argued that the generation of suspended particles can be avoided by using a large wire mesh cold trap in the cold leg (heterogeneous nucleation).

For the reference versions of the DCB the blanket itself represents no significant source of corrosion products. In this case the DCB corrosion of the steam generators (SG) surface (about 10^4 m^2) is of primary concern. Due to lower interface temperatures in the SG compared to the blanket, corrosion rates are much smaller (corrosion rates for T = 400°C are 20 % of those for T = 450°C, compare Eq. (4)). Nevertheless, an effective corrosion product removal system must be foreseen in the liquid metal loops /1.2/.

For the reference version of the DCB the inner surfaces of the blanket box including grids and grid plates are a source for corrosion. Additionally, the inner surface of the bubble extraction columns could contribute if it shows that the columns must be operated at temperatures of about 450°C /3.15/. A purification system must be also foreseen in order to avoid plugging in the narrow gap of the concentric inlet pipe, compare Fig. 1.8.

For the back-up design of the DCB the internal surface of the blanket (which is about the same for both blanket types) represents also a source for corrosion products. The corrosion rates per m^2 are expected to be significantly higher in the DCB than in the WCB due to the higher velocities. However, the effect of smaller velocities in the WCB might be compensated to a certain degree by larger interface temperatures at the grid plates and, for the back-up version of the WCB, the additional surface of the U-tubes (which has about the same value as that of the blanket box). Therefore the need of an efficient purification system is even more important for the back-up designs.

4. RATING OF MHD ISSUES

4.1 Rating methodology

In the course of the work of the Working Group MHD a rating methodology had been elaborated which appeared to be well suited for the MHD subject (Appendix A I). To a later date, the Blanket Coordination Group proposed a different methodology to be used in all working groups (A II). Therefore, in the following, this new methodology is applied.

The new methodology is based on the following steps:

1) Identification of issues
2) Weighting of each issue (numbers from 0 to 10)
3) Evaluation of each issue for each concept (from (+2) to (-2)).

Up to now, only the two Pb-17Li blankets were compared among each other. In the following, the aim is also the comparison of the two liquid metal blankets with the two ceramic blankets (BIT and BOT) for which MHD issues are not relevant.

4.2 MHD issues and weighting factors

The ranking has been performed both for the reference and the back-up designs of the DCB and WCB, see Table 4.1. First the characteristic MHD issues are listed for nominal operation which implies that the electrical insulation (if existing) is intact. The degradation of the insulator (which influences both pressure drop and transport processes) is listed as an extra issue.

Table 4.1 Ranking of MHD issues

a) DCB and WCB with direct coatings (reference design)

Issue	Weight-factor	Scores		
		DCB	WCB	BIT, BOT
nominal operation (undamaged coatings)				
- pressure drop	8	- 1.0	- 0.5	0
- heat transport	5	- 0.5	- 0.5	0
- tritium transport	5	0	- 0.5	0
- corrosion	6	- 0.5	- 0.5	0
degradation of insulator	10	- 2	- 0.5	0
Sum of weight factors x scores		-33.5	-17	0

b) DCB and WCB without direct coatings (back-up solution)

Issue	Weight-factor	Scores		
		DCB	WCB	BIT, BOT
nominal operation (undamaged coatings)				
- pressure drop	8	- 1.5	- 0.5	0
- heat transport	5	- 0.5	- 0.5	0
- tritium transport	5	0	- 0.5	0
- corrosion	6	- 0.5	- 0.5	0
degradation of insulator	10	- 1 - 1.5	- 0	0
Sum of weight factors x scores		-32.5	-12	0

The same weighting factors are used for the reference and the back-up design. This has the consequence that a high weighting factor attributed to an issue in one of the design options occurs also in the list of issues of the other design version.

MHD pressure drop is generally considered as a critical issue for purely self-cooled liquid metal blankets with electrically (thin) conducting walls. For the DCB, liquid metal is not used for heat transfer from the first wall which generally poses the most severe MHD problems. A weighting factor of 8 is selected because pressure drop for the DCB with FCIs is still an important issue. (If only the reference design were considered the weighting factor would have been lower).

MHD effects on heat and tritium transport processes are considered to be of average importance because

- in the DCB the heat is generated by volume heating, therefore, heat transfer from walls involved is no important issue (which would require the detailed knowledge of velocity distributions in the ducts).
- for the WCB the tritium transport is not expected to be endangered significantly by the occurrence of stagnant zones within the LM because the liquid metal convection is expected to be dominant compared to tritium diffusion.

MHD effects on corrosion are assessed to be of above average importance for the blankets without a direct coating because the generation of corrosion products in the blanket is of concern and deposition of corrosion products must be prevented.

The degradation of insulator is considered as a critical issue for the DCB because it might jeopardize the feasibility of this blanket type. Therefore, this issue weighted with the highest factor.

4.3 Evaluation of MHD issues

In the following the "alternative" interpretation (right hand side of Table 1 in A II) is used. Therefore, "0" corresponds to "not relevant or not applicable". In this sense the "0" is attributed to the BIT and BOT and also to the back-up version of the WCB for the issue "degradation of insulators". For relevant MHD issues then only negative scaling factors are given, however, besides (-1) and (-2) intermediate values (-0.5) and (-1.5) are also used.

4.3.1 Evaluation of MHD issues for the reference designs of the DCB and WCB

As mentioned earlier, the reference design of the DCB uses electrically direct coatings on all duct surfaces in the blanket whereas for the WCB only coatings on the water tubes are assumed.

Undamaged insulator

The total MHD pressure drop of the DCB is far below tolerable values ($<$ 0.7 MPa). There are some problems in respect to influences of 3d effects (e.g. due to nonideal directions of the magnetic field). These uncertainties do not influence remarkably the total pressure drop but require future investigations for the detailed design phase.

Pressure drop for the WCB is about 0.3 MPa, however, more MHD work is required in order to obtain the desired flow distribution in the gap of the inlet pipes and blanket header.

Heat transfer from walls within the PbLi is no issue for the DCB. There are some problems in respect to the transport of heat generated within the LM because unequal flow rates in parallel ducts may lead to unequal temperature distributions at the outlet. Due to the small pressure drop in the poloidal ducts the pressure drop in manifolds must be precisely known. More detailed investigations are required.

The optimization of heat transfer and heat transport within the WCB requires a better knowledge of the flow distribution within the blanket. There are uncertainties in the local pressure drop and concerning the influence of free convection. (The design value for the mean LM velocity in the blanket (required for tritium extraction) is about 3 mm/s; characteristic velocities due to free convection are assessed to be in the order of 10 cm/s) These influences might be so strong that the arrangement of the coolant tubes cannot be based on a design assuming only heat transfer by heat conduction.

Tritium transport within the blanket is no issue for the DCB because there is no possibility for tritium permeation into the water. Stagnant zones which could increase considerably the tritium inventory are not expected either. For the WCB, tritium transport is of some concern because free convection flow may influence significantly the interface temperatures which might increase the tritium permeation. Permeation rates could be also increased to a certain extent by PbLi zones with lower recirculation velocities.

Corrosion product generation and transport is of low concern for the DCB because the Al_2O_3 within the blanket has an excellent compatibility with PbLi and the corrosion rates in the steam generator are moderate due to the lower interface temperatures. However, an efficient purification system must exist in the LM loop which prevents the formation of suspended particles which might be trapped otherwise in the area of large magnetic field gradients (feeding pipes). For the WCB, corrosion of the uncoated grid plates is of some concern and deposition in the narrow gaps of the header must be prevented. Again, an efficient purification system must exist.

Degradation of insulator

The electrical degradation of the direct coating due to irradiation and thermal stresses represents a critical problem for the DCB because already a small area fraction of heavily degraded coating surface may lead to a nonacceptable blanket mode. The degradation of the insulator may occur due to irradiation effects but also because of thermal/mechanical stresses caused by changing blanket operation conditions or low-frequency MHD turbulence.

The insulator degradation poses some minor problems for the WCB because the alteration of local pressure drop will influence locally the velocity distribution and with this the heat and tritium transport conditions.

4.3.2 Evaluation of MHD issues for the back-up designs of the DCB and WCB

Undamaged FCI (DCB), no direct coating (WCB)

The pressure drop of the DCB with FCIs is considerably higher than that of the reference version (about 3 MPa for an optimized version compared to 0.7 MPa). This value still results in pressures far below maximum tolerable values. The total pressure drop is dominated by the pressure drop in the straight ducts which can be predicted with a high accuracy. Therefore, 3d effects and parallel duct effects play a smaller role than in the reference version. Nevertheless the pressure drop issue was evaluated to be of higher concern for the back-up solution because small percental uncertainties in the pressure drop assessment for the total blanket can still result in an absolute value which is not negligible. Further work is required to reduce these uncertainties. The pressure drop for the WCB is not significantly increased compared to the reference version. Again, some effort is required in respect to the optimization of the flow distribution at the blanket inlet.

Heat transport for the DCB is of even less concern than for the reference design because unequal flow rates in the ducts are unlikely to occur due to the dominant duct pressure drop. For the WCB the insufficiently known flow distribution within the blanket due to uncertain pressure drops and the influence of free convection requires future investigations for an optimized blanket design.

Tritium transport again is no relevant issue for the DCB. For the WCB, tritium transport is of similar concern as for the reference design.

Corrosion is of higher concern for the DCB compared to the reference version due to the higher corrosion rates of MANET in the blanket itself. Again it is mandatory that a purification system exists which prevents the formation of suspended particles. Corrosion is evaluated to be of lower concern for the WCB because of the significantly lower velocities. An efficient purification system is also required.

Degradation of FCI (DCB)

Compared to direct coatings, some degradation mechanisms do not exist or are significantly reduced (smaller thermal stresses within the FCI than in the blanket structure, cracks within the insulator might not lead to an insulator failure, a higher tolerable degradation of the electrical resistance (3 orders of magnitude)). Therefore, this issue is evaluated to be of somewhat less concern than for the reference design.

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APPENDIX I: ALTERNATIVE RATING METHOD

A.1.1 Rating methodology

In Table A.1 the individual issues are listed: "pressure drop", "heat", tritium transport" and "corrosion" for undamaged insulators, and the issue "degradation of insulators" (which influences both pressure drop and transport processes). Separate tables are used for the two blanket types. Each table, however, includes columns for both the reference and back-up version.

A ranking of these areas in respect to "importance" (I) and "uncertainty of assessment" (U) is performed. The combination of these two rankings leads to the ranking of the "level of concern" (C). A low "I" which a medium "U" might still result in a low "C" which means that the MHD influence in a certain area is not precisely known but the impact is so small that the open questions can be investigated e.g. during a system optimization in a quite late stage.

A medium "I" means that the MHD issue might be of interest in respect to blanket attractiveness. Together with a medium "U" then a medium "C" is obtained which means that this issue is not a critical issue but investigations in the nearer future are recommended (e.g. as separate or multiple effect tests in a medium test facility).

A high "I" can only result to a medium "C" if "U" is very low. In the other cases a high "C" is attached which means that this MHD issue is a "critical" issue where presently the feasibility of the blanket concept is not proven.

A.1.2 Dual Coolant Blanket

<u>Undamaged insulators</u>

- Pressure drop is of low importance for the reference design with di because the values are far below tolerable values. A medium uncertainty of assessment is attributed due to presently not well known influences due to 3-dimensional effects (e.g. because of nonideal directions of the magnetic field). However, it is expected that this uncertainty does not influence significantly the total pressure drop. Therefore, the level of concern is low. Pressure drop for the back-up solution with FCIs is of medium importance because the values are considerably higher and are of interest for the blanket attractivity. The assessment uncertainty is lower because the total pressure drop is dominated by the straight duct pressure drops and, hence, the influence of 3d effects is smaller. In total, a medium level of concern is attributed to this issue (ranking with a "x" was also considered).

- Heat transport is of medium importance for the reference version (di) because small differences to the design values of pressure drop of parallel ducts may alter with the flow rate and with this the heat transport. Due to "medium" uncertainties in the assessment of 3d effects this issue is of "medium" level of concern.
  For the FCI the heat transport issue is rated low because coupling effects between parallel ducts are small due to the dominant single duct pressure drop.
- The tritium transport issue is not relevant for both blanket versions since no tritium permeation in the blanket to the water loop can occur.
- Corrosion product transport is of low level of concern for the reference version because of the negligible corrosion rates in the blanket but of medium concern for the FCI version due to the higher rates.

Degradation of insulators

- The degradation of dc due to irradiation and thermal stresses is of critical importance because it might lead easily to a nonacceptable blanket operation mode. The uncertainties in predicting failure rates and healing effects are also high, therefore this issue is of high level of concern. Although the insulator degradation within the FCI is of smaller influence on pressure drop and maldistribution, the high uncertainty in predicting the degree of degradation still results in a high level of concern.

A.1.3 Water Cooled Blanket

Undamaged direct coating, no coating

- Pressure drop is supposed to be of no significant importance with or without coatings. Although there is some uncertainty in the pressure drop assessment, the level of concern is still low due to the small absolute values of the total pressure drop.
- Heat transport is of some importance for both versions because the influence of free convection migh alter remarkably the temperature

distribution compared to the present design based on pure heat conduction. Although the uncertainty is ranked medium, the level of concern is ranked low because the uncertainties can be reduced by design modifications and further experiments.

- Tritium transport is of some concern again due to the not sufficiently known influence of free convection. The permeation rate might be also increased to some extent by PbLi zones with higher residence times increasing the tritium concentration.
- Corrosion product transport considered to be still of low level concern for both versions although there are considerable uncertainties to predict corrosion rates from the grid plate structures.

Degradation of insulators (only relevant to reference version)

If the thermohydraulic design (including free convection flow) is based on the use of direct insulators on the water tubes then the degradation of these insulators will change locally the pressure drops. This alteration will influence heat and tritium transport conditions, therefore, this issue of some concern concern.

The results of the ranking methology described in this section agree farily well with those from Section 4. Some differences occur due to the different ranking scales.

Table A.I Ranking of MHD-issues for the two Pb17Li blankets

MHD-Issues of the Dual Coolant Blanket

Issue	Importance		Uncertainty of assessment		Level of concern	
	dc	FCI	dc	FCI	dc	FCI
pressure drop	x	xx	xx	x	x	xx
heat transport	xx	x	x	x	xx	x
tritium transport	nr	nr	nr	nr	nr	nr
corrosion prod. transport	x	xx	x	xx	x	xx
insulator degradation	xxx	xx	xxx	xxx	xxx	xxx

dc = direct insulating coating FCI = Flow Channel Insert
nr=not relevant
ranking: high: xxx, medium: xx, low: x

MHD-Issues of the Water Cooled Blanket

Issue	Importance		Uncertainty of assessment		Level of concern	
	dc	no c	dc	no c	dc	no c
pressure drop	x	x	xx	xx	x	x
heat transport	x	x	xx	xx	xx	xx
tritium transport	x	x	xx	xx	x	x
corrosion prod. transport	x	x	x	xx	x	x
Insulator degradation	x	nr	xx	nr	x	nr

dc = direct insulating coating on water tubes; no c = no coating at all
nr = not relevant
ranking: high: xxx, medium: xx, low: x

Blanket Concept Selection Exercise (BCSE) - Evaluation Methodology -

Introduction

During the Blanket Coordination Meeting (BCG-14) in Frascati on 28-3-95, the following system for the concept evaluation methodology was agreed. The system is derived from a number of proposals and is considered to be the most applicable for the comparative assessment of the four current blanket concepts. It will be used for the design evaluation in Working Group 1 and for the overall evaluation following the second workshop in Brasimone in June 1995. For consistency of the results, it should also be used - where practicable - by the other working groups.

STEP 1

In the first step all the issues that are relevant to the assessment of the four concepts will be identified. There should be a common list of issues against which all four concepts will be assessed.

STEP 2

The second step will be the definition of the scale to be used in the evaluation of the concepts for each issue. The scale running from +2 to -2 has been selected, as illustrated in the following table. Either of the columns describing the scale interpretation could be used, depending on the nature of the issue being assessed:

Table I

Scale for the evaluation of the issues for each concept

Rating	Rating interpretation	Alternative interpretation
+2	much better than average	no problems or very well suited
+1	better than average	well suited
0	average	not relevant or not applicable
-1	worse than average	some problems
-2	much worse than average	considerable problems or not suitable

STEP 3

The third step will be the definition of the scale to be used for the weighting of each issue. The following scale has been agreed:

Scale for the weighting of each issue

Weighting factor	Interpretation
10	extremely important
8	very important
6	above average importance
5	average importance
4	below average importance
2	of minor importance
0	no importance

It should be noted that intermediate values (e.g. 7 or 9) could also be used to distinguish between issues of similar importance.

STEP 4

The fourth step will be the determination of the weighting factor to be applied to each of the issues.

STEP 5

The fifth step will be the evaluation of the concepts against each of the issues, using the rating scale. The product of the rating result and the respective weighting factor will give the overall valuation for each concept and each issue.

STEP 6

The summation of the overall valuation figures for each concept will represent the final evaluation result.

With regard to the overall evaluation by the BCG and EFET, six main criteria were established; functionality, feasibility, safety and environmental impact, reliability/availability, development risks and costs. The criterion on costs will be assessed independently by EFET. As a result of the EFET involvement in the assessment, new working groups including EFET members were established for the evaluation of development risks and the compatibility of the blanket test modules with the ITER test environment. The original working groups should consequently not address these issues. The overall evaluation will be divided into four categories:

i) The relative suitability of the four concepts for a DEMO-type fusion reactor. Here, the working group results relevant to the first four criteria will be included, with a weighting factor, in the evaluation.

ii) Development risks.

iii) The compatibility of the blanket test modules with the ITER test environment

iv) Costs

The results of the evaluation in these four categories, together with an overall ranking, will be included in the final presentation to the FTSC-P.

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