MHD, Heat Transfer and Stress Analysis for the ITER Self-Cooled Blanket Design

X.R. Wang, E.A. Mogahed, I.N. Sviatoslavsky

October 1993

UWFDM-930

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

MHD, HEAT TRANSFER AND STRESS ANALYSIS FOR THE ITER SELF-COOLED BLANKET DESIGN

X.R. Wang,* E.A. Mogahed, and I.N. Sviatoslavsky

Fusion Technology Institute
University of Wisconsin-Madison
1500 Johnson Drive
Madison, WI 53706

November 1993

UWFDM-930

*Permanent Address: Southwestern Institute of Physics, P.O. Box 432, Chengdu, Sichuan 610041, P.R. China

ABSTRACT

Magnetohydrodynamic (MHD) effects of the liquid metal self-cooled blanket proposed for ITER are discussed in this paper. Scoping calculations of heat transfer, MHD pressure drop and structure stresses for the self-cooled lithium/vanadium inboard blanket design have been performed in order to show if the blanket option can meet the prescribed design criteria, or if modifications are required. The finite element computer code ANSYS™ is used to compute two dimensional temperature and stress distribution in the inboard blanket. The results of the investigation indicate that the ITER self-cooled lithium/vanadium blanket can satisfy the design criteria from the standpoint of heat transfer, MHD pressure drop and stresses. A comfortable safety margin can be obtained if insulating materials are used to decouple the conductive walls from the eddy currents resulting from the flow of liquid metals across magnetic fields.

INTRODUCTION

MHD effects in a self-cooled liquid metal blanket are critical issues influencing fluid flow, heat transfer and stresses. Because the coolant system pressure must exceed the pressure drop in order to circulate the liquid metal through the blanket, the system pressure must rise with increasing MHD pressure drop which induces severe stresses in the first wall and blanket. If the MHD pressure drop is very high, then the combined effect of the pressure stresses, thermal stresses and other loading conditions in the blanket could exceed the allowable stress for the structural material and may lead to eliminating the liquid metal self-cooled blanket design. Furthermore, MHD effects could influence thermal hydraulic performance by laminarizing the flow and lowering the heat transfer coefficients. For these reasons, a high MHD pressure drop is undesirable.

In recent years, efforts have been made toward understanding the MHD effects on heat transfer, pressure drop and thermomechanical problems of the liquid metal self-cooled blanket, and design solutions have been improved.[2-6] Some progress has been made in experimental and theoretical work on MHD flow and pressure drop in laminar duct flow.[7-11] New design solutions have been proposed in an attempt to exploit the benefits while alleviating the problems associated with liquid metals. Examples of these promising solutions include MHD flow tailoring, innovative use of insulating materials and dual lithium/helium cooling.[5,6,12,13,14]

A self-cooled blanket for ITER in which liquid lithium serves as both breeding material and coolant has been proposed.[13] This design option is based on the use of a simple poloidal flow channel with an insulating coating on the coolant channel walls for reducing the MHD pressure drop. Some preliminary analysis on the thermal hydraulics for this design option has been performed.[13-15] The major objective in this scoping analysis is to obtain a thermal hydraulic design window based on the maximum allowable structure temperature, stresses in the structure and the maximum MHD pressure drop in the blanket. The maximum allowable structure temperature determines the maximum value for the equilibrated coolant exit temperature for a given heat flux on the first wall. The maximum allowable stresses are related to the MHD pressure drop and the surface heat flux. Other parameters influencing the design window are neutron wall loading, coolant channel size, and the coolant inlet temperature. Any of these parameters can change the design window.

DESIGN DESCRIPTION AND REQUIREMENTS

Investigations by the ITER US JCT (joint central team) and home teams have shown that the self-cooled lithium blanket with a vanadium alloy structure and poloidal flow configuration has many advantages and is geometrically the simplest of all the design options considered.[3,13]

The design evaluated in this study is based on this option for ITER. A schematic layout of the inboard blanket is shown in Fig. 1. It consists of simple coolant channels with liquid lithium flowing in the poloidal direction perpendicular to the toroidal magnetic field. The first wall is 0.5 cm thick, the inboard blanket thickness is 45 cm and the poloidal flow path length is 12.5 m where the flow is subjected to an average toroidal magnetic field of 12 tesla.

It is well known that the interaction of the coolant velocity with the magnetic field results in the MHD effects on heat transfer and pressure drop. Principally, the MHD pressure drop is proportional to the coolant velocity, the magnetic flux density and the path length perpendicular to the magnetic field. It can be expected that a large pressure drop will exist in the ITER self-cooled inboard blanket if the coolant channel walls are not insulated, producing large stresses in the first wall and blanket. Furthermore, the velocity profile of the liquid lithium will be flattened by the strong toroidal magnetic field influencing the heat transfer coefficient and the temperature distribution. The aim of the scoping analysis for the ITER self-cooled blanket is to choose the best possible design parameters which will give satisfactory performance under the prescribed design constraints. The design constraints are:

1. The peak first wall temperature should be less than 500°C in order to allow for sufficient margin during power excursions.[13,15]
2. The interface temperature between the lithium and the vanadium structural material must not exceed 650°C.[3]

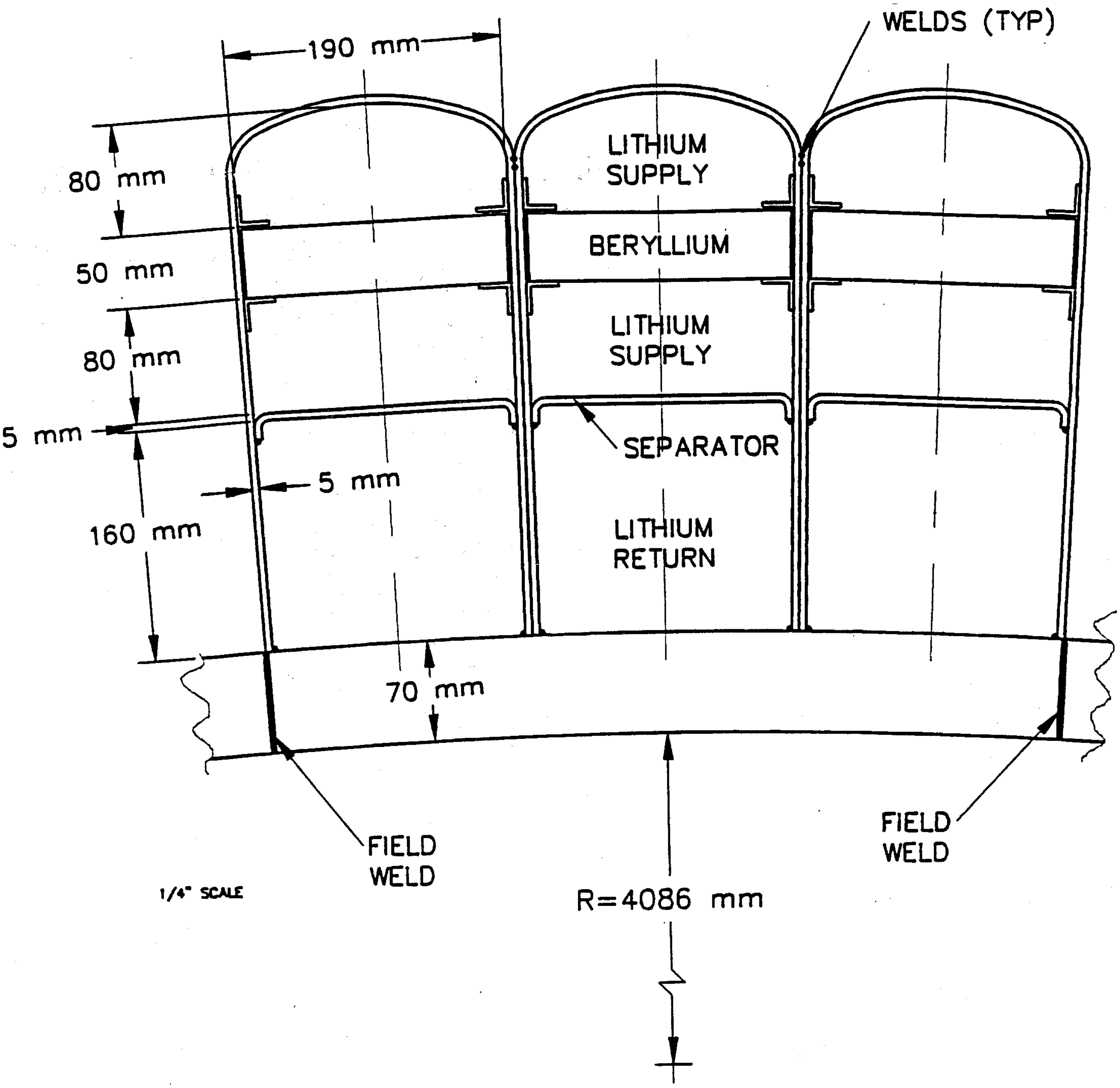

Fig. 1. Midplane cross section of an inboard module of the self-cooled Li/V blanket.

3. The peak structural material temperature must remain below the limiting value set by radiation effects, creep and other considerations (700°C for the vanadium structure).[3]
4. The total pressure drop should be less than 1.0 MPa in order to maintain a lower system pressure and lower stresses.
5. The primary and secondary stresses must remain below the limiting value prescribed by the ASME code, $\sigma_{primary} + \sigma_{secondary} < 3S_m$ (for the vanadium structural material, $S_m \approx 140.0$ MPa).[15]

HEAT TRANSFER IN THE SELF-COOLED BLANKET

The heat transfer and fluid flow of liquid metals in the presence of a strong magnetic field are quite different from conventional fluid flow. This so called MHD flow inherently possesses different characteristics, some of which are described below.

1. The flow of a liquid metal in the presence of a magnetic field is expected to be laminar, as any liquid metal turbulence in the blanket would be suppressed by the strong magnetic forces. This distinguishes liquid metal heat transfer from conventional systems where turbulent flow is unavoidable. The absence of eddy diffusivity in the blanket leaves only conduction as the remaining mechanism for heat transport perpendicular to the flow direction. It should be noted that upon entering a region of magnetic field, the liquid metal coolant retains a level of turbulence even in a very high magnetic field.[16] Obviously, the presence of turbulence in the liquid metal flow enhances heat, mass and momentum transport.
2. The velocity profile in the coolant channel tends to be flattened by the MHD effects. Such a uniform velocity profile is called slug flow and equations for such flow can be used in the heat transfer calculations. Since high velocity jets or side layers may exist in this MHD flow, they will greatly improve heat transfer and thus reduce the maximum interface and structure temperature.[2,3]
3. It is believed that even in regions where the velocity profile is fully developed, the temperature profile in the laminar flow requires very long distances to develop. The entire

length of the blanket is in the thermal entrance region. Research on this subject[2,3,16,17,18] shows that this conclusion will result in more efficient heat transfer in the first wall and blanket which, in turn, leads to lower structural temperatures than those predicted for fully developed thermal conditions.

4. The lithium coolant bulk temperature will be affected as some of the neutron energy is deposited directly in the coolant. The volumetric heat generation can alter the temperature distribution and heat transfer coefficient, and result in a higher film temperature drop. Fortunately, since liquid lithium has very good heat transfer characteristics, the heat transfer coefficient is high even at low velocity.
5. It is believed that highly nonuniform velocity profiles may exist in the liquid metal flow from the MHD effects, especially in regions of the blanket where the liquid metal flows through bends or transverse channels with varying flow areas or varying magnetic field. This unusual velocity profile would result in higher temperatures than expected and may produce hot spots.

Based on our current understanding of heat transfer behavior in liquid metal MHD flow, some assumptions must be made in order to simplify the heat transfer analysis for the ITER self-cooled inboard blanket. These assumptions are:

1. The velocity profile is assumed to be fully developed.
2. Any turbulent fluctuations in the blanket are effectively suppressed by the 12 tesla toroidal magnetic field.
3. Slug velocity profile is assumed because of the very high Hartmann number.
4. The effects of thermal entrance length are not considered in the calculation.
5. The Nusselt number is calculated by the correlation for fully developed flow.

The heat transfer based on these assumptions will reduce the thermal hydraulic window, and will result in conservative thermal hydraulic predictions because it neglects the presence of high velocity jets or side layers, and the effects of the thermal entrance length which enhance heat transfer.

Table 1

Thermal Hydraulic Input Parameters for the Self-Cooled Li/V Design Option (IB Blanket)

Fusion power, MW	1500
Neutron wall loading, MW/m^2	1.0
Surface heat flux, MW/m^2	0.1
Poloidal length, m	12.5
First wall thickness, m	0.005
Midplane radial thickness of IB blanket, m	0.45
Inlet temperature, ˚C	250

The temperature distributions in the first wall and blanket are performed by the finite element computer code ANSYS.[1] Some input parameters used in the computation are listed in Table 1.

MHD PRESSURE DROP

MHD Pressure Drop Equations

For fully developed slug flow perpendicular to the magnetic field, a simple MHD pressure drop equation can be obtained from the simultaneous solution of the Navier-Stokes equations for fluid motion and Maxwell's equations:[19,20]

$$\frac{dp}{dx} = - \frac{\mu v}{a^2}\left(\frac{H^2 \tanh H}{H - \tanh H} + \frac{H^2 C}{1 + C}\right) \qquad (1)$$

where

μ = fluid viscosity,

v = mean liquid metal flow velocity,

a = half-width of the coolant channel in the magnetic field direction

H = B a $(\sigma/\mu)^{1/2}$ dimensionless Hartmann number,

σ = the electrical conductivity of the liquid metal fluid, B = magnetic flux density perpendicular to the fluid flow,

$C = \frac{\sigma_w t_w}{\sigma a}$ wall conductivity ratio,

σ_w = wall electrical conductivity,

t_w = wall thickness.

For the ITER self-cooled inboard blanket design option, the Hartmann number is approximately given by $H = (12.0)\ a\ (3.49 \times 10^6/0.5 \times 10^{-3})^{1/2} \approx 3.8 \times 10^4$. Thus, equation (1) can be simplified in the following way

$$\frac{dp}{dx} = -\frac{\mu v}{a^2}\left(H + \frac{H^2 C}{1 + C}\right) \tag{2}$$

or

$$\Delta P = v\ L\ \sigma\ B^2 \left(\frac{1}{H} + \frac{C}{1 + C}\right). \tag{3}$$

In Eq. (3), L is the length of the coolant channel. In case of a thin conducting wall $1/H \leq C \leq 1$, Eq. (3) can be written in a simplified form:

$$\begin{aligned} \Delta P &= v\ L\ B^2\ \sigma\ C \\ &= v\ L\ B^2\ \sigma_w\ t_w/a\ . \end{aligned} \tag{4}$$

For non-conducting or insulated walls where $C \approx 0$, Eq. (3) becomes

$$\Delta P = \frac{v\ B^2\ L\ \sigma}{H} = \frac{v\ B\ L(\mu\ \sigma)^{1/2}}{a}\ . \tag{5}$$

The advantages resulting from the MHD flow in non-conducting walls are evident from the pressure drop (Eqns. 4 & 5) showing that the pressure drop is smaller by a factor of CxH ($C \sim 10^{-2}$, $H \sim 10^4$) in the case of non-conducting or insulated walls. A liquid metal self-cooled blanket based on this premise would exhibit a pressure drop at least two orders of magnitude lower than the case of thin conducting walls.

Three-dimensional MHD pressure drop effects are associated with the following cases: in the fringing magnetic field at the inlet and outlet of the blanket; in the transition region between the circular access tubes and the rectangular coolant channels; and in the U-shape bends at the bottom of the blanket. The semi-empirical equations for estimating the MHD pressure drop resulting from these three dimensional effects are described in the following:[21]

(For varying cross-section or varying magnetic field)

$$\Delta P = 0.2\ \sigma\ v\ a\ B^2\ (C)^{1/2} \tag{6}$$

(One leg of bend is parallel and the other is normal to the magnetic field)

$$\Delta P = \sigma\ v\ a\ B^2\ (C)^{1/2}\ . \tag{7}$$

It should be pointed out that there is a large uncertainty in the calculation of MHD pressure drops in the bends and changes in the cross-sections or in the magnetic field strength. However, these regions contribute only a small component of the overall pressure drop. The largest pressure drop component occurs in the rectangular poloidal channel perpendicular to the toroidal magnetic field. With the assumption of using the insulating coatings in the inboard blanket coolant channels, the pressure drop resulting from the three dimensional effects could be neglected.

Insulating Coatings

If the coolant channel walls perpendicular to the magnetic field are treated as membranes and the maximum internal pressure is approximately set equal to the pressure drop, the maximum mechanical stress would be normally proportional to the ratio of the channel-width to the thickness of the wall[4] (true only for circular channels!):

$$\begin{aligned}\sigma_{max} &= \frac{\Delta P_{MHD}\ 2a}{2t_w} \\ &= L\ B^2\ v\ \sigma_w\ . \end{aligned} \tag{8}$$

In this case, the mechanical stresses cannot be lowered by increasing the thickness of the channel walls as thick walls produce higher MHD pressure drops (see Eq. 4) requiring higher internal pressure. It appears that the only effective means to reduce stresses is to keep the coolant velocity low. However, the flow rate must be relatively high to remove heat and to maintain the temperature in the blanket within material and structural limits. Equation (8) also shows that for a given magnetic field strength, flow velocity and allowable stress, the coolant channel length perpendicular to the magnetic field L_{max} is limited by:

$$L_{max} = \frac{S_m}{B^2\ v\ \sigma_w}\ . \tag{9}$$

For the ITER self-cooled inboard blanket parameters, it is estimated that the maximum allowable coolant channel length is $L_{max} \approx 1/3\ v$ (m). This is a severe limitation on the design of a liquid metal self-cooled blanket. The only way to overcome this problem is to fully insulate the conductive walls from the eddy currents by the use of an electrically insulating layer or coating on the inside of the channel walls. This will result in at least two orders of magnitude reduction in the pressure drop (excluding the effects of the bends, manifold and other perturbations to the flow). The insulating layers or coatings must simultaneously possess good electrical insulating properties, compatibility with the liquid metal and radiation tolerance. The effects of radiation and lithium corrosion on the reliability of the insulating coatings are still uncertain. From the heat transfer and MHD pressure drop considerations, some selected properties of candidate ceramic insulators are listed in Table 2.

It is assumed that AlN may be used as the insulating coating material on the coolant channel walls of the ITER inboard blanket.[15] The required resistivity thickness product for the electrical insulation can be estimated from this equation:[22]

$$\rho_i\, t_w = \frac{B^2\, v\, L\, b}{\Delta P_{MHD}} \tag{10}$$

where ρ_i is the electric resistivity of the insulator; b is the half height of the coolant channel perpendicular to the magnetic field; ΔP_{MHD} is the MHD pressure drop resulting from the coolant flow through transverse magnetic field.

Table 3 gives the values of required insulator properties and the thickness of the electric insulating coating for different cases of coolant temperature rise. Even if we set the tolerable pressure drop in the blanket at 0.1 MPa, since the MHD pressure drop due to three-dimensional effects and access tubes is not taken into consideration, the required insulation properties and the thickness of the insulating coatings would still be very low. It should be emphasized that the development of acceptable insulating coatings is perceived as a key development issue for self-cooled blankets.

Table 2

Properties of Some Candidate Ceramic Insulators[15]

	BeO	MgO	AlN	BN
Melting point, °C	2570	2800	2230	3000
Density, kg/m^3	3010	3580	3050	2270
Electrical resistivity, Ω-m	10^8	10^9	10^5	5×10^9
Thermal conductivity, W/m-°C	550	11.5	22.0	5.0
Thermal expansion coefficient, 10^{-6}/°C	8.0	13.0	5.0	12.5

Table 3

Thickness Requirement for Insulating Coating

Coolant temperature rise, °C	50	75	100
MHD pressure drop, MPa	0.24	0.17	0.12
$\rho\ t_W$ (Ω-m^2)	0.528×10^{-3}	0.536×10^{-3}	0.54×10^{-3}
t_W (10^{-9} m)	5.28	5.36	5.4

THERMOMECHANICAL ANALYSIS

The stresses in the first wall and blanket mainly result from the coolant pressure, surface heat flux on the first wall and volumetric heat generation. From Eq. (8), it can be seen that the maximum pressure stresses are independent of the wall thickness. As described above, the insulating coating on the inside of the channel walls leads to a negligible MHD pressure drop, leading to low coolant pressure and pressure stresses. Eq. (8) also shows that the pressure stresses increase linearly with the flow rate. For a given heat input, the flow rate is determined by the allowable temperature rise of the lithium between the blanket inlet and outlet. This temperature rise is limited by the peak first wall temperature and the peak temperature at the Li/V interfaces as dictated by corrosion considerations.

We can determine these parameters by first writing the energy balance equation:

$$Q = W \rho C_p (T_{exit} - T_{inlet}) \tag{11}$$

where Q is the total thermal power, W the volumetric flow rate of the coolant, ρ and C_p the density and specific heat of the coolant, respectively. T_{exit} is the coolant exit temperature and T_{inlet} is the coolant inlet temperature.

The coolant velocity is:

$$v = \frac{Q}{A C_p \rho (T_{exit} - T_{inlet})} \tag{12}$$

and Eq. (8) can be rewritten in the following form:

$$\sigma_{max} = \frac{Q L B^2 \sigma_w}{A C_p \rho (T_{exit} - T_{inlet})} \tag{13}$$

where A is the cross-sectional area of the coolant channel. It simply shows that the pressure stresses are closely related to the thermal hydraulic parameter ΔT and thermal power in the blanket.

It is well recognized that in order to properly model a problem to compute the stresses one should correctly account for the existing structural constraints. However, it is difficult to accurately simulate the real mechanical boundary conditions which are dependent on detailed structural design, module fabrication and processing, and module support connections. In this stress analysis, two different mechanical boundary conditions are assumed. As shown in Fig. 2, the boundary conditions in Case 1 are more severe than in Case 2. The pressure loading mainly comes from the results of the MHD pressure drop calculation with an additional 0.25 MPa to obtain the absolute pressure. The remaining loadings are due to surface heat on the first wall and nuclear bulk heating in the structure and breeding material.

NUMERICAL CALCULATIONS AND RESULTS

Scoping calculations have been performed to obtain a consistent result between thermal hydraulics, MHD pressure drops and stress calculations to determine whether the ITER

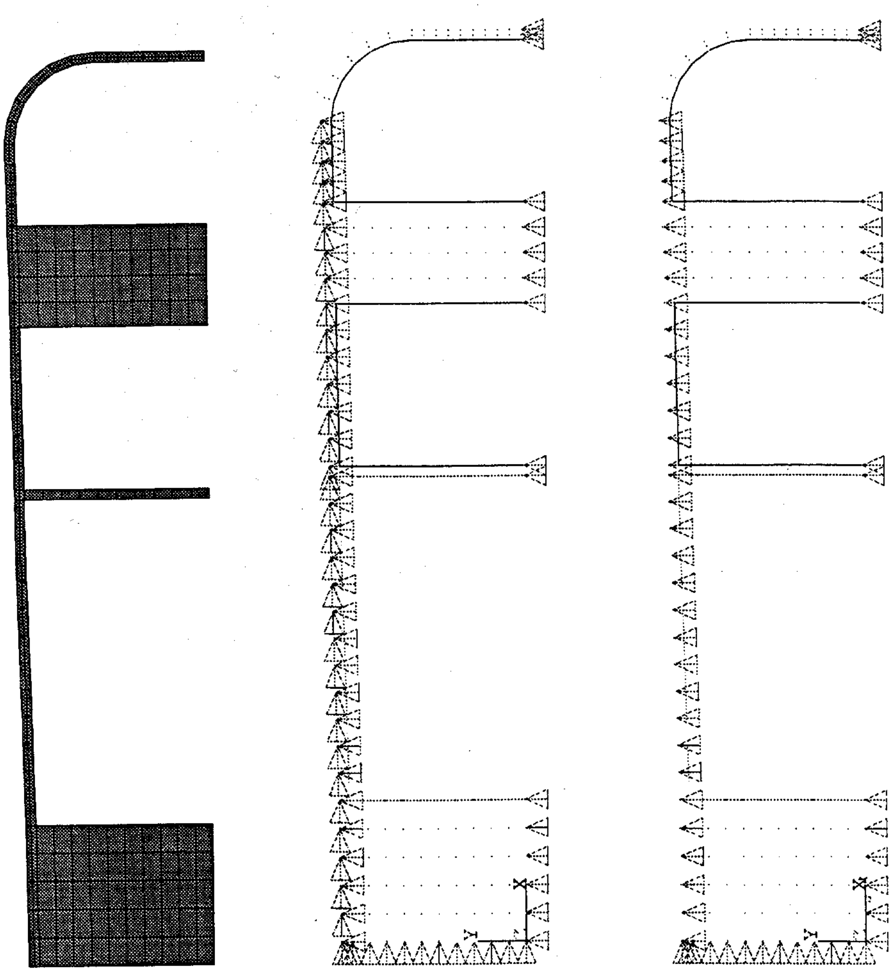

Fig. 2. The elements of the inboard blanket module and mechanical boundary conditions.

Table 4

Comparison of Thermal-Hydraulic Performance Parameters for the Self-Cooled Li/V Design Option

Fusion Power 1500 MW, Surface Heat Flux 0.1 MW/m^2

	$\Delta T=50$	$\Delta T=75$	$\Delta T=100$
Inlet temperature, °C	250	250	250
Exit temperature, °C	300	325	350
Peak FW temperature, °C	320	338	362
Peak structural material temperature, °C	505	535	563
Peak Li/V interface temperature, °C	336	352	380
Average coolant temperature at bottom (U bend), °C	286	305	563
Average velocity, front channel, m/s	1.76	1.16	0.87
Average velocity, back channel, m/s	1.79	1.19	0.90
Volumetric flow rate, m^3/s	7.31	4.85	3.62
Pressure drop, MPa	0.24	0.17	0.12

self-cooled inboard blanket is likely to meet the design criteria set for it, or whether modifications will be needed. Two dimensional temperature and stress distributions have been performed by using the finite element computer code ANSYS.[1]

As discussed above, the coolant inlet and exit temperatures are common parameters for determining the MHD pressure drop, heat transfer and stresses. These two parameters also affect the thermal efficiency of the fusion reactor. The temperature distribution in the first wall affects the thermal stresses and the MHD pressure drop affects the pressure stresses in the blanket structure. Tables 4 and 5 give the comparisons of the thermal hydraulic performance parameters for the ITER self-cooled inboard blanket design under different levels of fusion power and surface heat flux. The summary of the stress calculations at the nominal power of 1500 MW is

Table 5

Comparison of Thermal-Hydraulic Performance Parameters for the Self-Cooled Li/V Design Option

Fusion Power 2000 MW, Surface Heat Flux 0.4 MW/m^2

	ΔT=50	ΔT=75	ΔT=100
Inlet temperature, °C	250	250	250
Exit temperature, °C	300	325	350
Peak FW temperature, °C	405	424	450
Peak structural material temperature, °C	572	600	629
Peak Li/V interface temperature, °C	327	356	385
Average coolant temperature at bottom(U bend), °C	292	305	326
Average velocity, front channel, m/s	2.21	1.66	1.24
Average velocity, back channel, m/s	2.25	1.69	1.27
Volumetric flow rate, m^3/s	9.22	6.91	5.18
Pressure drop, MPa	0.35	0.23	0.17

given in Table 6. The analysis at 2000 MW of fusion power has been made to determine whether this design can sustain such a power excursion. The results are summarized in Table 7. Figure 2 shows the elements of the inboard blanket module and the mechanical boundary conditions. Figure 3 shows the temperature distribution at different surface heat fluxes and Fig. 4 shows the stress distribution.

Calculations have also been performed under different coolant temperature rises and different heat fluxes in order to obtain a design window. The results are summarized in Tables 8 and 9. Figures 5 and 6 show the design window and the design limits as a function of surface heat flux. It can be seen that the major design constraint is the peak first wall temperature. The design margin is comfortable in spite of the conservative assumptions which have been made.

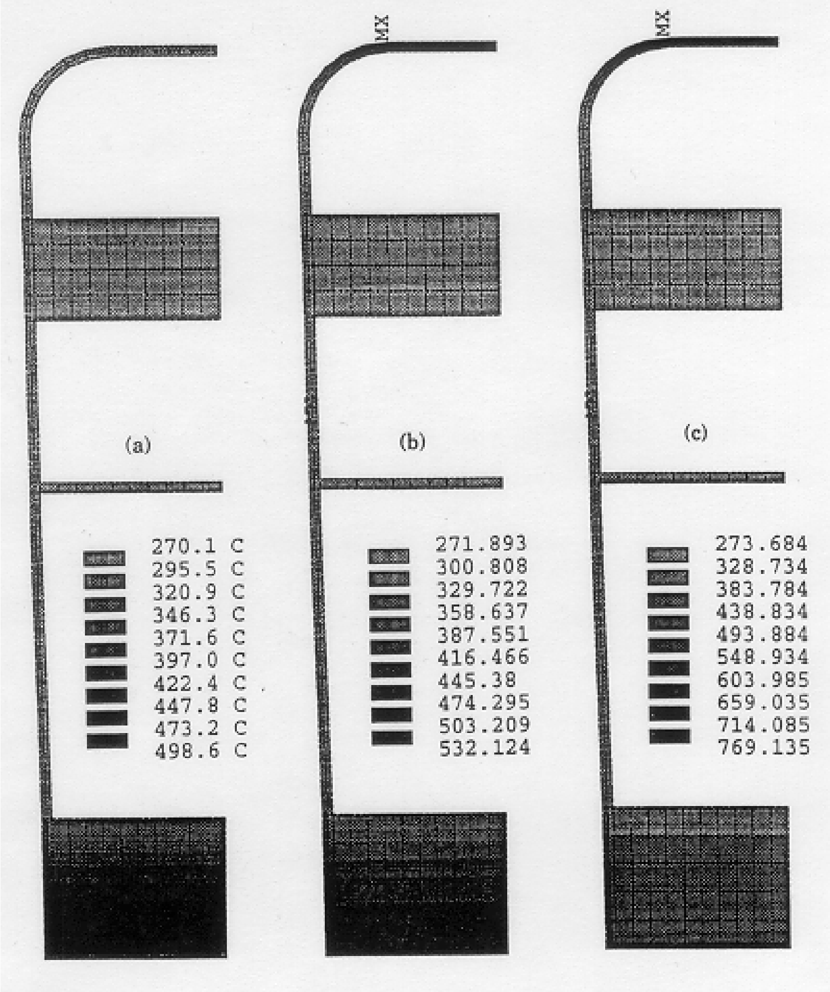

Fig. 3. The temperature distributions of the inboard blanket module under different surface heat flux: (a) $q_s = 0.1$ MW/m^2, (b) $q_s = 1.0$ MW/m^2, (c) $q_s = 2.0$ MW/m^2.

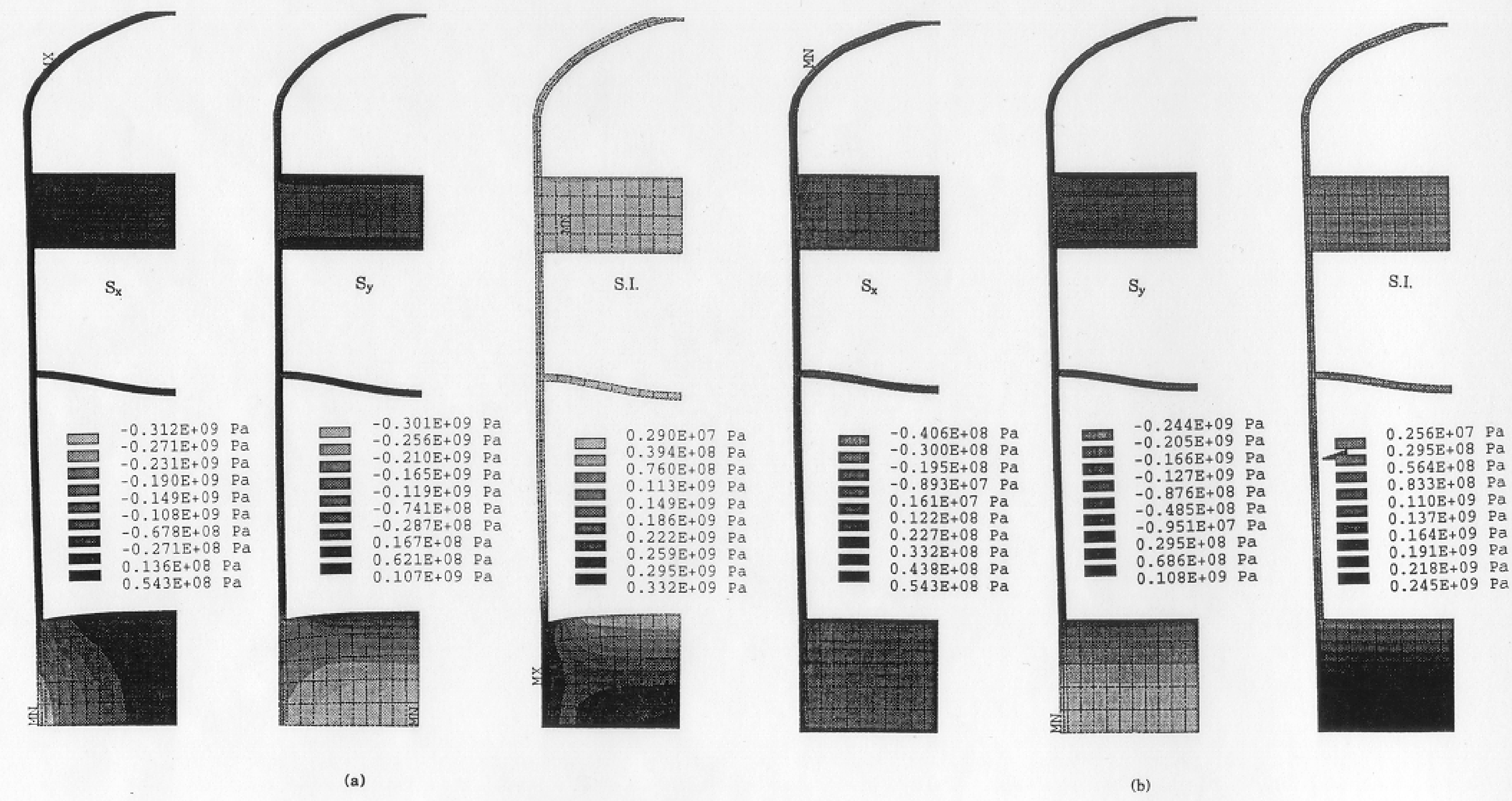

Fig. 4. The stress distribution of the inboard blanket module under different boundary conditions: (a) Case 1, (b) Case 2.

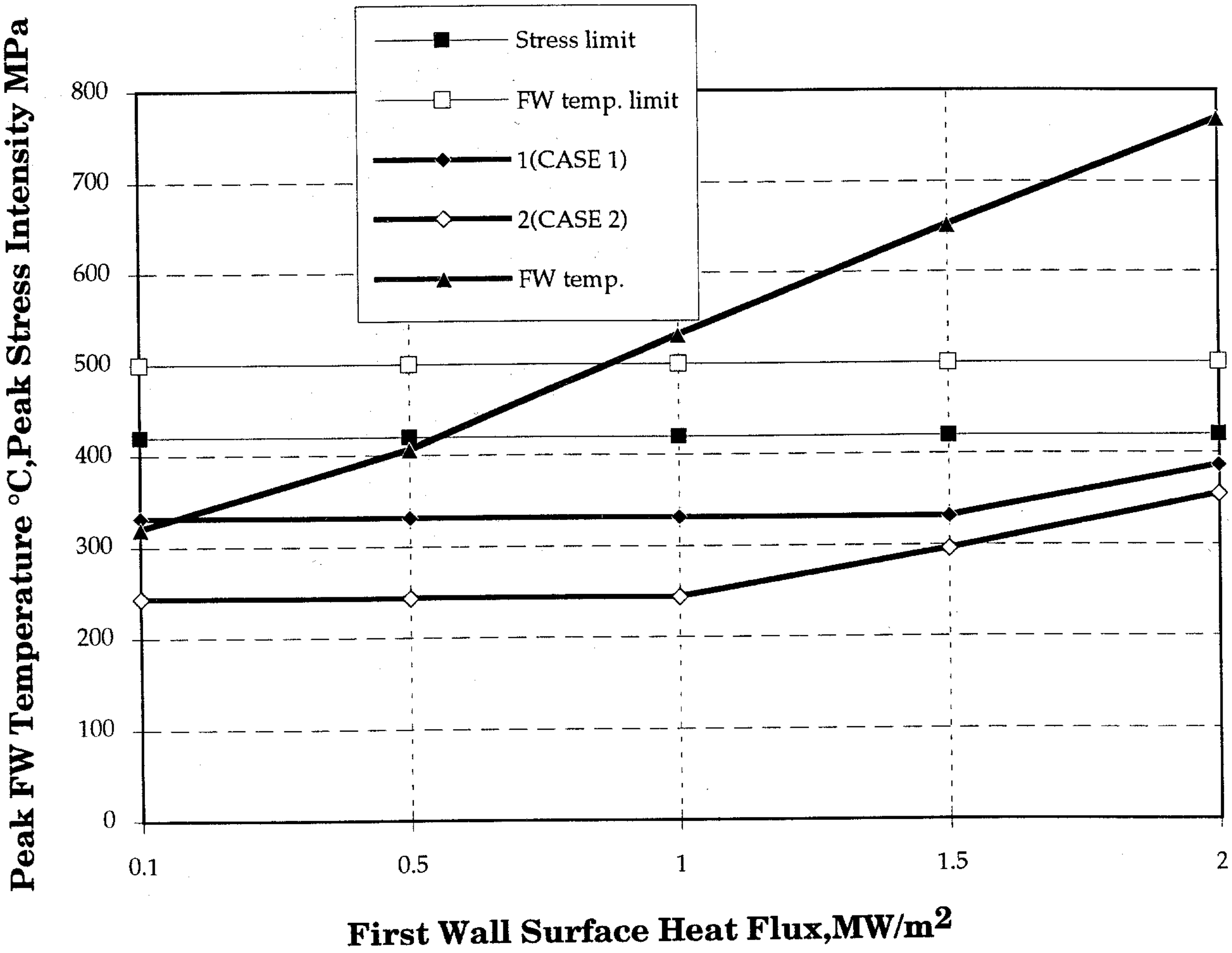

Fig. 5. Variation of the peak temperature in the first wall and stress intensity in the blanket as a function of surface heat flux, ΔT=50°C.

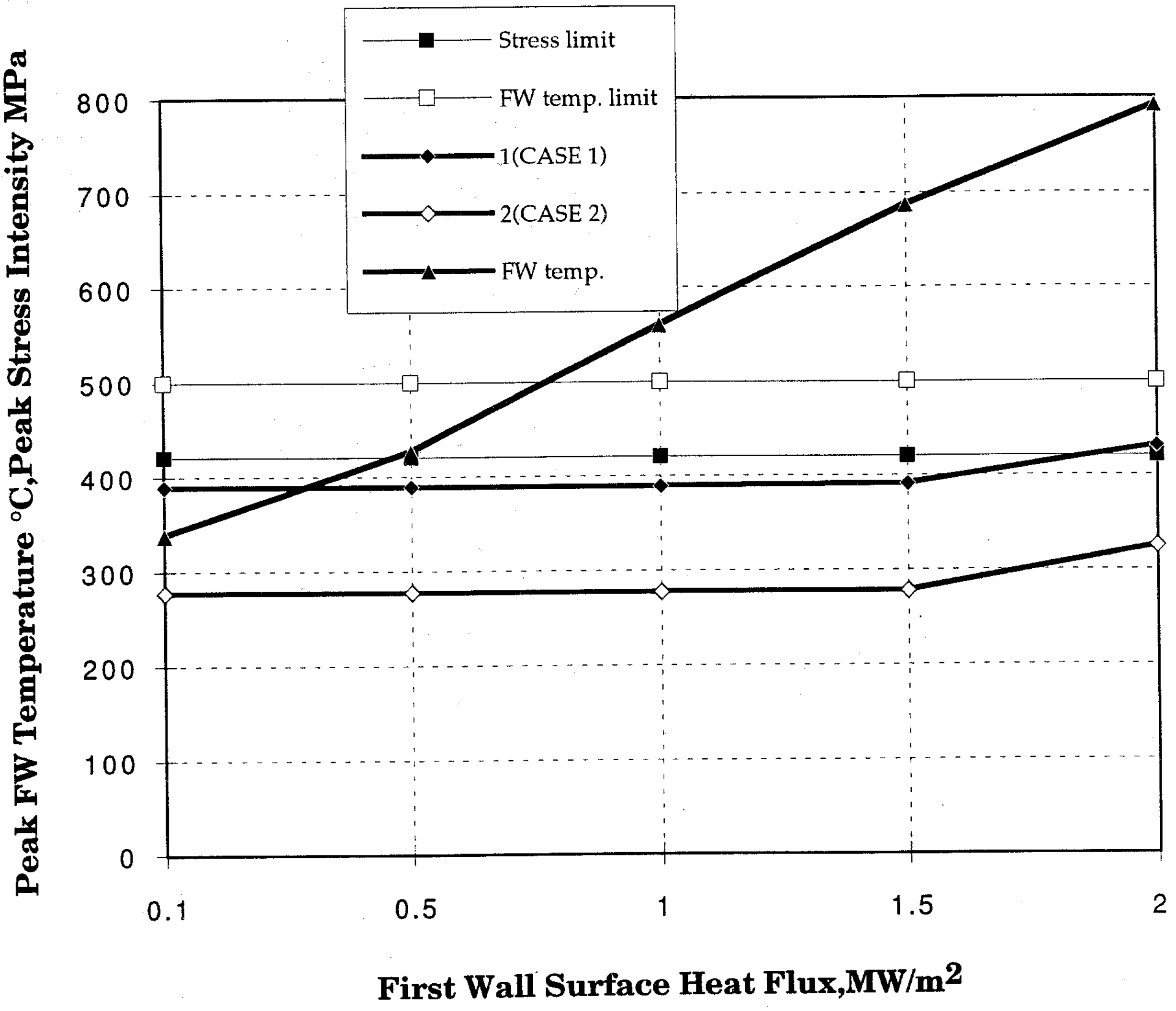

Fig. 6. Variation of the peak temperature in the first wall and stress intensity in the blanket as a function of surface heat flux, ΔT=75°C.

Table 6

Summary of Stress Analysis for the Self-Cooled Li/V Design Option (IB Blanket)

Coolant Pressure at Midplane, Fusion Power 1500 MW, Heat Flux 0.1 MW/m^2

	ΔT=50	ΔT=75	ΔT=100
*Case 1**			
Maximum tensile stress, MPa			
Radial direction	54.3	47.5	44.1
Toroidal direction	107.0	92.1	85.1
Maximum compressive stress, MPa			
Radial direction	312	354	396
Toroidal direction	301	343	384
Maximum shear stress, MPa	142	163	185
Maximum stress intensity, MPa	332	389	473
Maximum displacement, 10^{-3} m	0.54	0.49	0.48
*Case 2**			
Maximum tensile stress, MPa			
Radial direction	54.3	47.8	44.8
Toroidal direction	100.0	92.4	85.5
Maximum compressive stress, MPa			
Radial direction	40.6	35.8	33.6
Toroidal direction	244	276	309
Maximum shear stress, MPa	56.0	49.0	45.7
Maximum stress intensity, MPa	245	277	310
Maximum displacement, 10^{-3} m	0.66	0.69	0.77

**Case 1*: Most severe boundary condition. At side of the sub-module, both radial and toroidal directions are fixed (see Fig. 2).

Case 2: Only toroidal direction is fixed (see Fig. 2).

Table 7

Summary of Stress Analysis for the Self-Cooled Li/V Design Option (IB Blanket)

Coolant Pressure at Midplane, Fusion Power 2000 MW, Heat Flux 0.4 MW/m^2

	ΔT=50	ΔT=75	ΔT=100
*Case 1**			
Maximum tensile stress, MPa			
Radial direction	75.7	66.7	61.4
Toroidal direction	135.0	118.0	107.0
Maximum compressive stress, MPa			
Radial direction	502	538	580
Toroidal direction	486	522	563
Maximum shear stress, MPa	233	251	272
Maximum stress intensity, MPa	527	653	737
Maximum displacement, 10^{-3} m	0.85	0.77	0.74
*Case 2**			
Maximum tensile stress, MPa			
Radial direction	77.8	71.3	69.0
Toroidal direction	134	117	105
Maximum compressive stress, MPa			
Radial direction	60.0	55.6	54.3
Toroidal direction	391	419	451
Maximum shear stress, MPa	78.0	68.6	62.9
Maximum stress intensity, MPa	393	420	454
Maximum displacement, 10^{-3} m	1.12	1.33	1.34

**Case 1*: Most severe boundary condition. At side of the sub-module, both radial and toroidal directions are fixed.

Case 2: Only toroidal direction is fixed.

Table 8

Summary of Stress Analysis for the Self-Cooled Li/V ITER Design Option (IB Blanket)

(Coolant Pressure at Midplane, ΔT = 50.0°C, Fusion Power 1500 MW)

Surface heat flux, MW/m^2	0.1	0.5	1.0	1.5	2.0
MHD pressure drop, MPa	0.24	0.32	0.39	0.47	0.54
<u>*Case 1*</u>*					
Maximum tensile stress, MPa					
Radial direction	54.3	76.9	104	137	170
Toroidal direction	107	143	192	245	298
Maximum compressive stress, MPa					
Radial direction	312	311	311	311	311
Toroidal direction	299	299	300	300	300
Maximum shear stress, MPa	142	142	142	142	153
Maximum stress intensity, MPa	332	332	332	332	386
Maximum displacement, 10^{-3} m	0.54	0.76	1.00	1.25	1.49
<u>*Case 2*</u>*					
Maximum tensile stress, MPa					
Radial direction	54.3	76.9	104	137	170
Toroidal direction	108	142	192	245	298
Maximum compressive stress, MPa					
Radial direction	40.6	59.9	85.1	115.0	144.0
Toroidal direction	243	243	243	244	244
Maximum shear stress, MPa	56.0	77.5	102	128	153
Maximum stress intensity, MPa	243	243	244	296	355
Maximum displacement, 10^{-3} m	0.66	0.87	1.12	1.38	1.62

**Case 1*: Most severe boundary condition. At side of the sub-module, both radial and toroidal directions are fixed.

Case 2: Only toroidal direction is fixed.

Table 9

Summary of Stress Analysis for the Self-Cooled Li/V ITER Design Option (IB Blanket)

(Coolant Pressure at Midplane, ΔT = 75.0°C, Fusion Power 1500 MW)

Surface heat flux, MW/m^2	0.1	0.5	1.0	1.5	2.0
MHD pressure drop, MPa	0.17	0.21	0.26	0.32	0.38
<u>*Case 1*</u>*					
Maximum tensile stress, MPa					
Radial direction	47.5	68.1	98.8	132	163
Toroidal direction	92.1	125	171	220	274
Maximum compressive stress, MPa					
Radial direction	354	354	354	355	355
Toroidal direction	343	343	343	343	343
Maximum shear stress, MPa	163	163	163	163	163
Maximum stress intensity, MPa	389	389	389	391	431
Maximum displacement, 10^{-3} m	0.55	0.69	0.93	1.18	1.39
<u>*Case 2*</u>*					
Maximum tensile stress, MPa					
Radial direction	47.8	68.3	99.4	132	163
Toroidal direction	92.4	124	170	220	274
Maximum compressive stress, MPa					
Radial direction	35.8	53.6	82.5	112	140
Toroidal direction	276	276	276	276	276
Maximum shear stress, MPa	49.0	68.4	91.2	116	141
Maximum stress intensity, MPa	277	277	277	278	325
Maximum displacement, 10^{-3} m	0.69	0.89	1.14	1.39	1.63

**Case 1*: Most severe boundary condition. At side of the sub-module, both radial and toroidal directions are fixed.

Case 2: Only toroidal direction is fixed.

SUMMARY AND CONCLUSIONS

The problems arising from the MHD effects on the thermal hydraulics and thermomechanics of the ITER self-cooled lithium blanket design option can be overcome by using insulating coatings on the coolant channel walls. If AlN ceramic material is used for the insulating coating, the present design which has 0.24 MPa of the MHD pressure drop (assuming a ΔT of 50°C) requires an insulator resistance of 5.28×10^{-4} Ω-m^2, and a thickness of only 5×10^{-9} m. Assuming that such a coating can be made and maintained, the ITER self-cooled lithium inboard blanket design can satisfy the design criteria from the standpoints of heat transfer, MHD pressure drop and stresses. Under nominal operating power, the design shows a comfortable safety margin and a wide design window. During a power excursion from 1500 MW to 2000 MW, the peak temperature in FW is well below the allowable, and the maximum stress intensity can meet the stress limits only if the module is not constrained in the radial direction.

ACKNOWLEDGEMENT

Support for this work has been provided by the U.S. Department of Energy.

REFERENCES

1. G.J. DeSalvo and R.W. Gorman, "ANSYS Engineering Analysis System User Manual," Reversion 4.4, May 1989, Swanson Analysis Systems, Inc.
2. M.A. Abdou, et al., "FINESSE: A Study of the Issues, Experiments, and Facilities for Fusion Nuclear Technology Research and Development (Interim Report)," PPG-821, UCLA-ENG-84-30 (May 1984).
3. D.L. Smith et al., "Blanket Comparison and Study-Final Report," ANL/FPP-84-1, Argonne National Laboratory (Sept. 1984).
4. S. Malang et al., "Self-Cooled Liquid-Metal Blanket Concept," *Fusion Technol.*, **14** (Nov. 1988).
5. M.A. Abdou et al., "Thermal, Fluid Flow, and Tritium Release Problems in Fusion Blankets," *Fusion Technol*. **18** (Sept. 1990).
6. L. Barleon, V. Casal et al., "MHD Flow in Liquid Metal-Cooled Blanket," *Fusion Engineering and Design*, **14** (1991).
7. K. Miyazaki et al., "Reduction of MHD Pressure Drop of Liquid Metal Flow by Insulation, Part I: Insulated Circular Ducts," F*usion Technol.*, **19** (May 1991).
8. K. Miyazaki et al.," Reduction of MHD Pressure Drop of Liquid Metal Flow by Insulation, Part II: Three-Face Insulated Rectangular Ducts," *Fusion Technol.*, **19** (May 1991).
9. T.Q. Hua and J.S. Walker, "MHD Considerations for Poloidal-Toroidal Coolant Ducts of Self-Cooled Blanket," *Fusion Technol.*, **19** (May 1991).
10. A.Y. Ying and M.S. Tillack, "MHD Heat Transfer in Elongated Rectangular Ducts for Liquid Metal Blankets," *Fusion Technol.*, **19** (May 1991).
11. T. Kunugi, M.S. Tillack and M.A. Abdou, "Analysis of Liquid Metal MHD Fluid Flow and Heat Transfer Using the KAT Code," *Fusion Technol.*, **19** (May 1991).
12. H. Madarame, "Trend in Liquid Metal Breeder Blanket Development," *Fusion Engineering and Design*, **17** (1991).

13. Y. Gohar, "ITER First Wall, Blanket, and Shield Design Activity," Presented at ITER Blanket/Shield Workshop, ITER Co-Center Garching, Germany, March 13-April 6, 1993.
14. D.K. Sze et al., "MHD Considerations for a Self-Cooled Liquid Lithium Blanket," *Fusion Technol.*, **21** (May 1992).
15. T.Q. Hua, "MHD and Thermal Hydraulic Analysis of the Self-Cooled Blanket," Unpublished paper supplied by author, Argonne National Laboratory, July 1993.
16. K. Taghavi et al., "Special Features of First-Wall Heat Transfer in Liquid-Metal Fusion Reactor Blanket," *Fusion Technol.*, **12** (July 1987).
17. T. K Unugi and M.Z. Hasan, "Entry-Length Effect on the Thermal-Hydraulic Design Components of Fusion Reactor, Part I: Non-MHD Flow," *Fusion Technol.*, **19** (May 1991).
18. M.Z. Hasan and T. Kunugi, "Entry-Length Effect on the Thermal-Hydraulic Design Components of Fusion Reactor, Part II: MHD Flow," *Fusion Technol.*, **19** (May 1991).
19. J.C.R. Hunt and R. Hancox, "The Use of Liquid Lithium as Coolant in a Toroidal Fusion Reactor, Part I: Calculation of Pumping Power," CML-R115, University of Chicago (1971).
20. M.A. Hoffman and G.A. Carison, "Calculation Techniques for Estimating the Pressure Losses for Conducting Fluid Flows in Magnetic Fields," UCRL-51010, Lawrence Livermore National Laboratory (1971).
21. F. Najmabadi et al., "The TITAN Reversed-Field Pinch Fusion Reactor Study, Final Report," UCLA-PPG-1200 (1990).
22. S. Malang, "Pressure Drop in the Liquid Metal Breeder Loop for the Tritium Extraction in Gas-Cooled Blanket," Unpublished paper supplied by author, June 9, 1993.