Thermomechanical Analysis of a Blanket with Liquid $Li_{17}Pb_{83}$ Breeder for an Experimental Fusion Reactor

M. Biggio
Commission of the European Communities, J.R.C. Ispra Establishment, Engineering Division, I-21020 Ispra (Varese), Italy

C. Piana
Politecnico di Milano, CESNEF, Piazza Leonardo da Vinci 32, I-20133 Milano, Italy

Summary

In a machine such as INTOR*, the main function of the blanket is to breed tritium in order to reduce the need for an external supply. The liquid eutectic $Li_{17}Pb_{83}$ alloy has been proposed as breeder material. At the JRC Ispra, a reactor blanket was designed based on the use of this alloy. This blanket was conceived in the form of movable segments, placed side-by-side around the plasma. Each segment is composed of stainless steel vessels, containing the breeding material and the light water cooling system. A blanket segment is also provided with a radiation panel (first wall) cooled by an independent cooling water system.

The paper reports the thermomechanical analysis of such a blanket in normal operation. For this condition, two- and three-dimensional calculations of temperature and stress distribution in the wall of a vessel were performed using the finite element method. The calculations were performed for the blanket in AISI 316 type as structural material both with and without radiation panel. From the calculated results it appears that a radiation panel is necessary despite a significant lowering of the local breeding ratio. An alternative solution with ferritic high alloy steel has been investigated for access if a radiation panel can be dispensed with. This solution appears to be satisfactory (ASME-CODE CASE No. 47) from the point of view of maximum stress and hence of the estimated life-time of INTOR ($7 \cdot 10^5$ cycles).

A parametric analysis by RSM (Response Surface Methodology) was also performed to assess with simplified polinomial expressions the vessel stress and temperature response with different materials and thermal loads.

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* INTOR, INternational TOkamak Reactor.

1. Introduction

In the framework of the studies performed at JRC Ispra for the Experimental Power Fusion Reactor INTOR/ NET, a number of different breeding blanket solutions were proposed with solid and liquid breeder materials. One proposal involved the eutectic $Li_{17}Pb_{83}$ which looks attractive with its main following advantages:

- high local breeding ratio, due to the homogeneous dispersion of lead in the lithium;
- low chemical reactivity with water; this represents an important advantage from a safety point of view;
- very low solubility of tritium in the alloy permits low tritium inventories in the blanket.

Owing to these attractive data, a blanket conceptual design based on $Li_{17}Pb_{83}$ has been carried out. The main features of the blanket are shown in Fig. 1. This blanket is designed in the form of vessel units, provided with radiation panels and arranged in the poloidal and toroidal directions, and located inside the main toroidal vessel of the machine, which represents the plasma boundary. This type of structure is assessed by taking into account:

a) degradation of the material due to irradiation damage;
b) reduction in thickness due to sputtering, melting and vaporisation;
c) the thermomechanical behaviour under cyclic thermal stress.

This paper, therefore, limits its attention to the thermomechanical behaviour of the blanket assuming as structural materials stainless steel AISI 316 type and ferritic high alloy steel. The thermomechanical analysis is performed by finite element computation of temperature and stress distributions for both two- and three-dimensional cases. A parametric analysis by RSM was also carried out.

2. Blanket Description

The blanket consists of 24 moveable segments placed side-by-side around the plasma. Each of them is formed of 24 vessel units arranged in 6 adjacent rows disposed side-by-side in toroidal direction. Each row contains 4 vessel units of similar size disposed in poloidal direction (Fig. 1). For each segment a single inlet/outlet cooling circuit is provided, collecting the cooling tubes in the blanket units arranged as shown in Fig. 2. The connection of a blanket unit to the main shielding structure (vacuum vessel) of the machine is also shown in the same figure. This connection was designed so as to allow thermal dilatation and to minimize thermal stress under the transients of reactor operation. The $Li_{17}Pb_{83}$ circulates at low speed through a separate circuit to the outside for continuous tritium removal. The blanket is also provided (reference design) with a first wall (radiation panel). This radiation panel is made up of a series of tubes, facing the plasma and separated from the blanket units, as shown in Fig. 1. These tubes are arranged along the toroidal direction and they are cooled by heavy water through an independent circuit. Fig. 1 shows the arrangement of the inlet/outlet collectors for the first wall cooling tubes as well as their attachment to the vacuum vessel. The tubes are free to dilate in the toroidal direction. A set of parameters for the first wall and blanket units is shown in Table I.

3. Temperature and Stress Computation

Thermomechanical analysis was performed on the main feature shown in Fig. 1, considering the most loaded vessel unit (the central one, facing the plasma). The main dimensions of this unit are: height 1.4 m, width 0.304 m, depth 0.4 m, the wall thickness is 8 mm. The temperature and stress computation for the vessel unit in AISI 316 stainless steel with radiation panel was carried out. The analysis for the vessel unit without radiation panel has been done both for AISI 316 and for ferritic steel in order to assess the best solution. The calculations were performed under the following main assumptions:

a) the vessel unit was considered in steady (not pulsed) conditions, subjected to the maximum (flat top) thermal loading shown in Table II. The surface heating is entirely absorbed by the radiation panel in the reference design;
b) inlet/outlet coolant temperatures: 240°C and 260°C, respectively (at 5 MPa pressure);
c) heat transfer coefficient between cooling water and tube wall: 25,000 $W/m^2 {}^\circ C$ (corresponding to 3.3 m/sec flow velocity);
d) constant thermal conductivity for liquid $Li_{17}Pb_{83}$ breeder: 15.9 $W/m^\circ C$;
e) temperature dependent data for structural materials as shown in Table III;
f) perfect conductivity between steel and liquid $Li_{17}Pb_{83}$.

Two- and three-dimensional calculations of temperature and stress distributions were performed by the finite element method using the codes FLHE(1) and BERSAFE(2), respectively.

3.1 Two-dimensional Calculations

Two-dimensional calculations were performed for half of the vessel cross-section (due to structural and loading symmetry) (Fig. 3), to obtain the temperature distributions in the $Li_{17}Pb_{83}$, in the wall of cooling tubes and in the wall of the vessel. An estimation of the stress distribution in the SS wall of the vessel was also performed. A set of proper conditions has therefore been imposed to account for geometrical and loading symmetry. The above structure was analysed using 750 type-EP16(1,2) elements and 2700 nodes. The highest temperatures, equivalent Von Mises stresses and displacements are presented in Table IV. Typical plots of temperature and Von Mises stress in the breeder and in the vessel wall are shown in Fig. 4, for the design case with radiation panel.

3.2 Three-dimensional Calculations

The calculations were carried out considering the vessel unit wall shown in Fig. 2. Only half (due to structural and loading symmetry) of the vessel unit has been considered, assuming that it was free to expand both in the toroidal and in the poloidal directions according to real constraints.

As heat deposition was assumed to vary monodimensionally and the variation of the cooling water temperature of the blanket unit along the poloidal direction is very small (maximum ΔT from the top to the bottom of the vessel unit is about 5°C), the temperature distribution in each cross-section of the vessel (Fig. 2) has been supposed to be the same. According to this assumption, the 3-D stress analysis of the vessel unit was performed, considering each wall cross-section of the module loaded by the temperature distributions obtained in two-dimensional analysis. The structure was analysed using 252 type-EZ60(1,2) elements and 2700 nodes. The highest temperature, Von Mises stresses and displacements are presented in Table V. Fig. 5 shows a plot of the deformed structure for the design case with radiation panel.

4. Parametric Analysis by RSM (Response Surface Methodology)

To assess the role played by the most important parameters affecting the vessel stresses and temperatures (i.e. heat deposition, surface heating and stainless steel thermal characteristics), use has been made of a special technique, called Response Surface Methodology (RSM)(3,4,5). This methodology builds up a polynomial form in the parameters mentioned above which fits the obtained results as well as possible. A quadratic form using the STEPWISE regression procedure(5) has been chosen. In this case the number of necessary results is given by the following expression:

$$N = 2^{np} + 2n_p + 1 \quad (4)$$

where n_p is the number of selected parameters. Input data for RSM have been taken from 2-D calculation results obtained by the finite element method. For maximum temperatures either in SS or in $Li_{17}Pb_{83}$, three parameters have been selected with respective ranges:

- maximum heat deposition [W/cm³]: 11.5 ÷ 27
- surface heating [W/cm²]: 0.0 ÷ 30
- thermal conductivity K [W/cm°C] : 0.15 ÷ 0.30

For maximum stresses a thermal expansion coefficient $\alpha[10^{-6}\,{}^\circ C^{-1}] = 10 \div 22$ has also been considered. The polynomial form obtained for maximum temperature in both SS and $Li_{17}Pb_{83}$ was:

$$T_{max}[^\circ C] = \beta_1\phi_n + \beta_2\phi_s + \beta_3 K + \beta_4\phi_n K + \beta_5\phi_s K + \beta_6 K^2 + \beta_7 \qquad (1)$$

with: ϕ_n = max SS heat deposition; ϕ_s = surface heating and K = thermal conductivity.
The $\beta_1, ..., \beta_7$ values are given in Table VI for T_{max} in SS and in $Li_{17}Pb_{83}$, respectively. The polynomial form for the maximum stress in SS is:

$$\sigma_{max\ SS}[MPa] = \beta_1\phi_n + \beta_2\phi_s + \beta_3 K + \beta_4\alpha + \beta_5\phi_s K + \beta_6\phi_s\alpha + \beta_7 K^2 + \beta_8 K\alpha + \beta_9\phi_s K\alpha + \beta_{10} \qquad (2)$$

where α is the thermal expansion coefficient and the values from β_1 to β_{10} are given in Table VI. In the above expression all the parameters (ϕ_n, ϕ_s, K and α) must be taken in the normalized range ($-\sqrt{2} \div \sqrt{2}$). Figs. 6 to 8 show the behaviour of temperature and stress as functions of selected parameters. These results are obtained employing heat deposition values related to the design case with radiation panel.

5. Conclusions

In the foregoing the thermomechanical behaviour of liquid $Li_{17}Pb_{83}$ breeder blanket for an experimental INTOR-type fusion reactor has been described. It is concluded that:

. The comparison between the results shows that, for all the designs (with and without radiation panel), the highest equivalent Von Mises stress in three-dimensional calculation is about 3.5 times the highest value obtained in two-dimensional calculations. This is due to the bending moment which results from the non-uniform temperature distribution on each cross-section of the module. This bending moment cannot be taken into account by two-dimensional calculations.

. The reference design with radiation panel seems to be feasible. The ASME code$^{(6)}$ for AISI 316 at 367°C and with alternating stress from $\sigma_{min} = 0$ and $\sigma_{max} = 110$ MPa allows more than 10^6 cycles. This value exceeds the estimated life of INTOR ($7 \cdot 10^5$ cycles)$^{(7)}$. Moreover with the arrangement and size of the cooling tubes shown in Figs. 2 and 3, the maximum temperature of $Li_{17}Pb_{83}$ is within prescribed AISI 316 stainless steel compatibility limits$^{(8)}$.

. The design in AISI 316 without radiation panel at 488°C and with an alternating stress from $\sigma_{min} = 0$ to $\sigma_{max} = 332$ MPa can stand about $3 \cdot 10^3$ cycles (ASME CODE$^{(6)}$). The maximum temperature of $Li_{17}Pb_{83}$ (433°C) exceeds prescribed AISI 316 stainless steel compatibility limits$^{(8)}$, even if restricted to a small zone facing the plasma.

. The design in ferritic steel without radiation panel at 458°C and with an alternating stress from $\sigma_{min} = 0$ and $\sigma_{max} = 152$ MPa can stand more than 10^6 cycles (ASME CODE$^{(6)}$). However, no experimental data exist, to our knowledge, on maximum temperature on the ferritic steel-$Li_{17}Pb_{83}$ compatibility and on potential stress corrosion or liquid metal embrittlement effects.

. From the results of parametric 2-D analysis by RSM it appears that stress and temperature behaviour are almost linear as functions of the selected parameters (thermal loads and material characteristics). To obtain the maximum stress in 3-D geometry it is sufficient to multiply the expression (2) (para. 4) by the factor 3.5.

. The results of the present analysis are clearly dependent upon the assumptions made. Therefore, although trends can be observed, the results obtained are subject to uncertainties such as those associated with creep, swelling, vaporisation and the time-dependent effects of irradiation on material properties. This type of information requires more detailed analysis of the behaviour of fusion reactor blankets, and it is hoped that future studies will provide opportunities to continue with this work.

6. Acknowledgements

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References

[1] FULLARD, K., "FLHE Phase 2", Central Electricity Generating Board, Research Department, Berkeley Nuclear Laboratories, Report RD/B/N286, Jan. 1974.

[2] HELLEN, T.K., "Bersafe Phase II (Level 1)", Central Electricity Generating Board, Research Department, Berkeley Nuclear Laboratories, Report RD/B/M2508, May 1974.

[3] BOX, G.E.P. and HUNTER, J.S., "Multifactor Experimental Designs for Exploring Response Surface", Ann. Math. Statist. 28 (1957) 195.

[4] LISANTI, B., "Una Applicazione della RSM all'Analisi Sperimentale di un LOCA in un PWR", Doctorate Thesis, Pisa (Italy) University, 1980. Unpublished.

[5] OLIVI, L., "RSM Handbook for nuclear Safety Analysis, Part 2, Program Library", Technical Note No. 1.05.01.82.56, May 1982, Commission of the European Communities, JRC Ispra Establishment, Italy.

[6] ASME-Boiler and Pressure Vessels - Code base N. 47, Elastic Analysis.

[7] INTOR (International Tokamak Reactor) Phase One. Int. Atomic Energy Agency, Vienna, 1982.

[8] COEN, V., FENICI, P., KOLBE, H., ORECCHIA, L., SASAKI, T., "Compatibility of AISI 316L Stainless Steel with the $Li_{17}Pb_{83}$ Eutectic", J. of Nucl. Mat. 110 (1982), pp.108-114.

TABLE I - $Li_{17}Pb_{83}$ INTOR blanket parameters

First wall	
Type	panel of tubes
Arrangement	toroidal
Coolant	D_2O
Structure	AISI 316
Tube ID, mm	10
Tube thickness, mm	variable, 12 mm plasma side 3 mm rear side
Coolant temp., °C	50 - 100
Max. structure temp., °C	350

Breeder region	
Type	vessel units
Arrangement	poloidal
No. of units in a segment	24
Size : rectangular with circular shape in front of plasma	
Coolant in tubes	H_2O
Tube ID/OD, mm	18-21
Coolant temp., °C	240-260
Coolant press., MPa	5
Breeder thickness, cm	40
Vessel thickness, mm	8
Local tritium breeder ratio	1.20
Net tritium breeding ratio	0.72

TABLE II - Thermal loading in the vessel unit

Thermal loading	With radiation panel	Without radiation panel
Surface heating, W/cm^2	no surface heating	12
Heat deposition, W/cm^3		
- vessel wall	simple exponential decreases from 11.5 plasma side to 0.3 rear side	simple exponential decreases from 14 plasma side to 0.4 rear side
- breeder	compound exponential decreases from 17.5 plasma side to 0.3 rear side	simple exponential decreases from 14 plasma side to 0.4 rear side

TABLE III - Temperature dependent data for structural materials

Material	Temperature T (°C)	Thermal conductivity K (W/m°C)	Thermal expansion α (1/°C)	Elastic modulus E (MPa)	Poisson's ratio ν
AISI 316	21	14.5	$15.46 \cdot 10^{-6}$	195,100	0.290
	537	21.5	$20.52 \cdot 10^{-6}$	155,100	0.316
Ferritic	100	27.6	$10.13 \cdot 10^{-6}$	190,000	0.290
	600	26.4	$12.15 \cdot 10^{-6}$	150,000	0.316

TABLE IV - 2-D max temperatures, Von Mises stresses and displacements

	Vessel in AISI 316 with radiation panel	Vessel in AISI 316 without radiation panel	Vessel in ferritic steel without radiation panel
Temp., °C - vessel wall	367	488	458
- breeder	354	433	418
Von Mises stress (vessel wall), MPa	32	100	42
Displacement (x/y), mm (vessel wall)	2.2/–0.84	2.6/–0.9	1.5/–0.5

TABLE V - 3-D max temperatures, Von Mises stresses and displacements

		Vessel in AISI 316 with radiation panel	Vessel in AISI 316 without radiation panel	Vessel in ferritic steel without radiation panel
Temp., °C	- vessel wall	367	488	458
	- breeder	354	433	418
Von Mises stress (vessel wall), MPa		110	332	152
Displacement (x/y/z), mm (vessel wall)		3/−0.8/−7.4	4.4/−2.4/−8.8	2.4/−1.2/−5.0

TABLE VI - Polynomial forms coefficients for maximum temperatures and stress calculations

	β_1	β_2	β_3	β_4	β_5	β_6	β_7	β_8	β_9	β_{10}
T_{max} in SS	55.52767	102.3333	−25.619	−2.9237	−10.52875	5.574487	580.2336			
T_{max} in $Li_{17}Pb_{83}$	51.36304	65.68903	−7.11055	−1.44873	−1.34625	0.81699	517.2856			
σ_{max} in SS	6.71077	38.9564	−20.2068	23.43212	−8.7579	10.40769	4.68042	−5.28193	−2.2944	84.6755

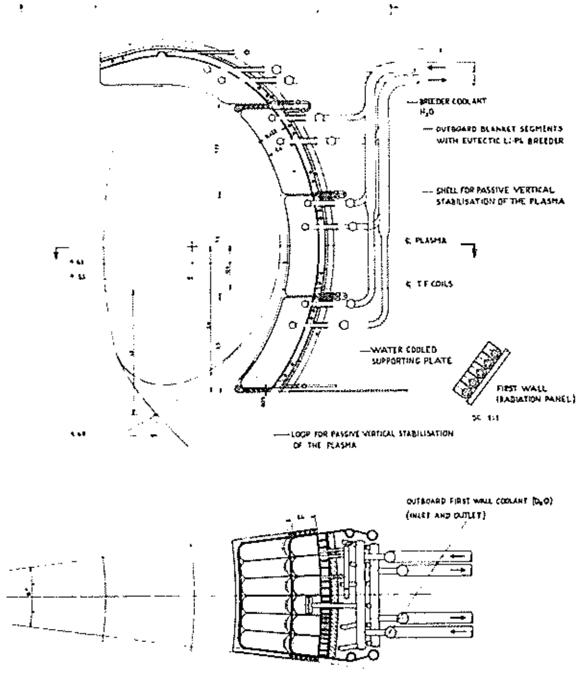


Figure 1 - INTOR/NET blanket with $Li_{17}Pb_{83}$ breeder

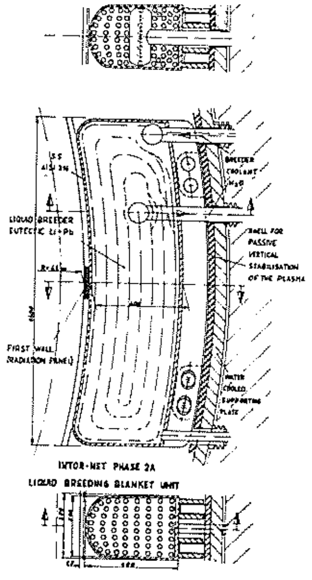


Figure 2 - Blanket element with $Li_{17}Pb_{83}$ breeder

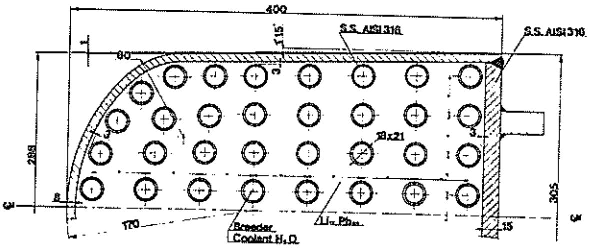
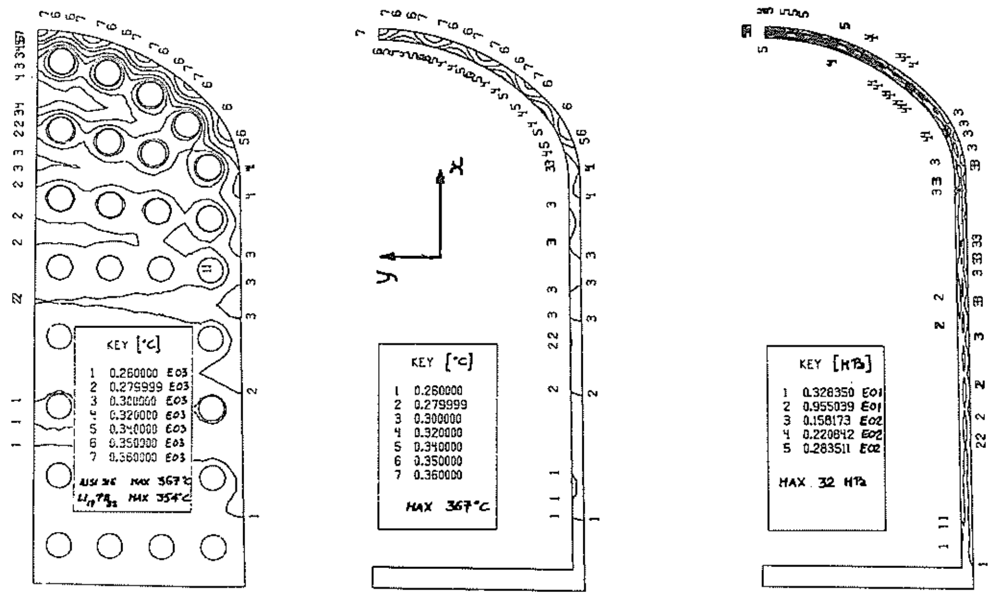


Figure 3 - Half cross section of the blanket vessel unit



a) temperature plot in $Li_{17}Pb_{83}$

b) temperature plot in the wall

c) Von Mises stress plot

Figure 4 - 2-D temperature and stress plots in the vessel unit cross-section (with radiation panel)

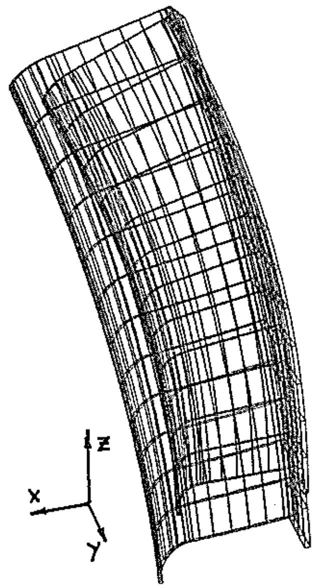


Figure 5 - 3-D undeformed and deformed configurations of the vessel unit wall (with radiation panel)

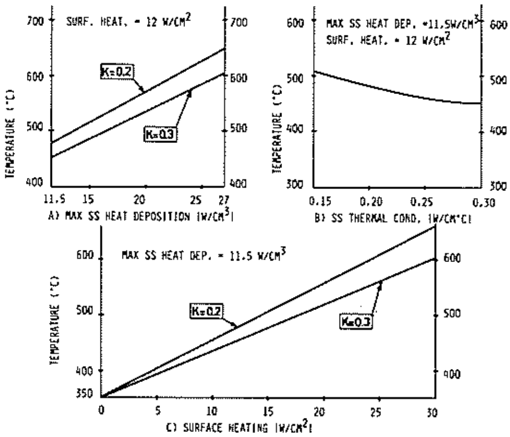


Figure 6 - SS max temperature

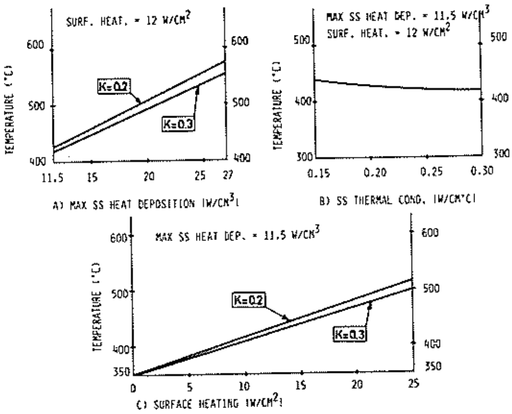


Figure 7 - $Li_{17}Pb_{83}$ max temperature

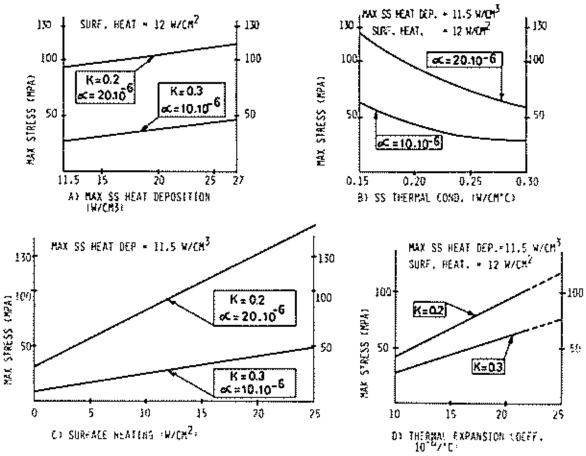


Figure 8 - SS max stress (2D - calculation)