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SAND-83-1654c
Conf-830795--1

SAND--83-1654C

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PRELIMINARY DESIGN ANALYSIS OF THE ALT-II
LIMITER FOR TEXTOR*

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ABSTRACT

Installation of a large toroidal belt pump limiter, Advanced Limiter Test II (ALT-II), on the TEXTOR tokamak at Juelich, FRG is anticipated for early 1986. This paper discusses the preliminary mechanical design and materials considerations undertaken as part of the feasibility study phase for ALT-II.

Since the actively cooled limiter blade is the component in direct contact with the plasma edge, and thus subject to the severe plasma environment, most preliminary design efforts have concentrated on analysis of the blade. The screening process which led to the recommended preliminary design consisting of a dispersion strengthened copper or OFHC copper cover plate over an austenitic stainless steel base plate is discussed. A 1 to 3 mm thick low atomic number coating consisting of a graded plasma-sprayed Silicon Carbide-Aluminum composite is recommended subject to further experiment and evaluation. Thermal-hydraulic and stress analyses of the limiter blade are also discussed.

*This work performed at Sandia National Laboratories supported by the U.S. Department of Energy under contract number DE-AC04-76DP00789.

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I. Introduction

The objective of the Advanced Limiter Test-II (ALT-II) is to place a toroidal-belt pump limiter into the TEXTOR tokamak at Juelich, FRG early in 1986. Results from ALT-II would then be available in time to aid in the design of toroidal-belt pump limiters for the next generation of research-oriented tokamaks. In a companion paper, Conn et al. [1], describe the concepts and theoretical considerations which underlie the ALT-II design. The purpose of this paper is to describe the engineering aspects of the current ALT-II design, and to discuss the engineering and materials concerns which have influenced the design. Preliminary analyses have concentrated on the limiter blade, since this is the portion of the limiter in direct contact with the plasma edge. Specifically, the paper discusses three areas of engineering design: materials selection and fabrication, thermal-hydraulic analyses, and stress analyses. A third paper by Deksnis and Mioduszewski [2] discusses the pumping alternatives under consideration.

As shown in Figure 1, two design alternatives are under consideration. The advantages and disadvantages of each alternative are discussed from the conceptual viewpoint in Reference 1. Design evolution and modification are expected to continue as additional studies and experiments such as the ALT-I [3] experiment are completed.

II. Design Criteria

Major design parameters for ALT-II are listed in Tables 1 and 2 of Reference 1. In addition to the specific numerical design parameters, some general design precepts were adopted for the engineering analysis. First, where possible, the

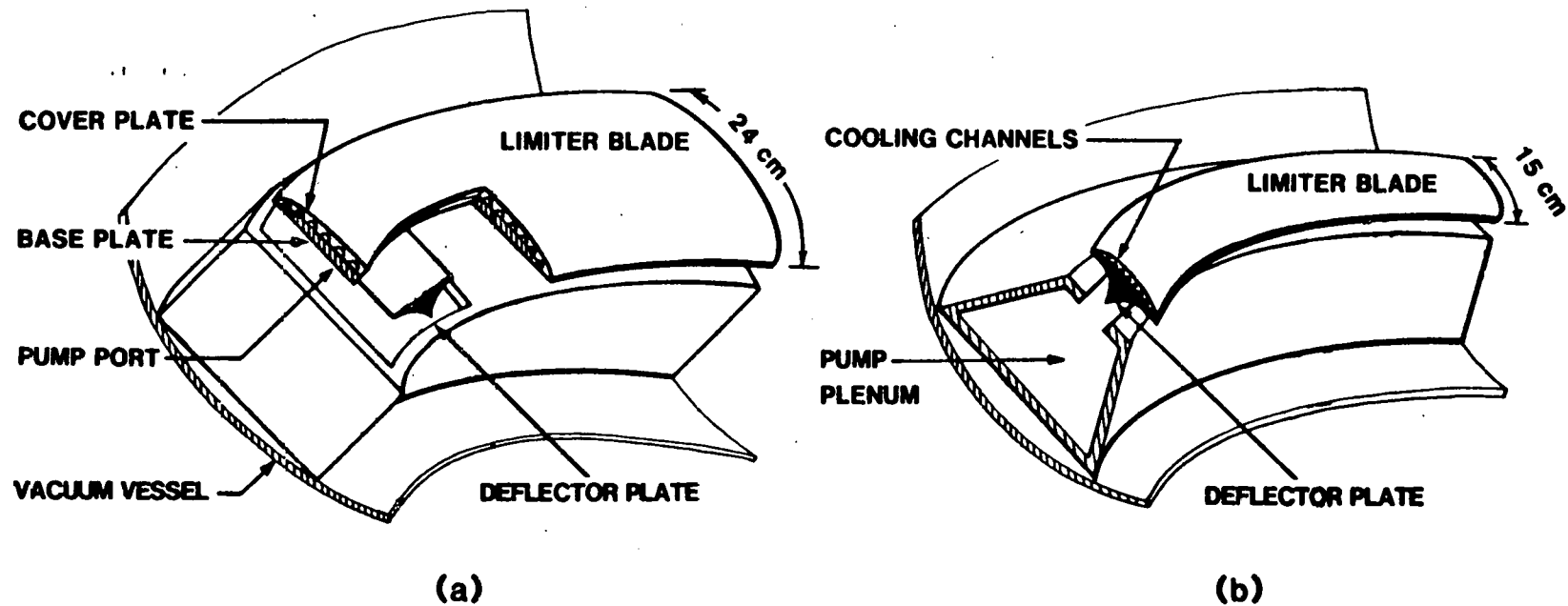


Figure 1. Alternative ALT-II Limiter concepts. In (a) divertor plates scatter neutralized particles into pump duct. For (b) a long divertor plate scatters neutralized particles into toroidal collection plenum.

design should be relevant to the future design of net-power-producing tokamaks. Thus some common current techniques and materials were excluded; e.g., passively-cooled graphite limiters were eliminated because of potential chemical erosion problems. This desire for reactor relevance is constrained by the current state of knowledge of material properties in the D-T fusion environment, and by fabrication limitations imposed when only a few prototype limiters are to be produced.

III. Materials Selection and Fabrication

A. Limiter Blade

Figure 1 schematically illustrates cross-sections of the current ALT-II limiter concepts. As shown, the limiter blade is 15 or 24 cm wide, approximately 1 to 2 cm thick and contains a series of machined cooling channels. Depending on the final design, individual segments of the limiter blade will either be approximately 1/3 m or 1 m long. From the fabrication, electromagnetic force, and critical heat flux viewpoints the 1/3 m long limiter section is preferred.

The limiter, especially in the proximity of the cover plate, must be able to withstand temperatures in the range 200-300°C for up to 50 hrs, which will be accrued through the summation of many 2-10 s tokamak pulses. From a materials viewpoint the exposure temperature is critical, because the mechanical properties of many materials degrade sharply over this temperature range. For example, the yield strength of full hard OFHC copper is 380 MPa, 280 MPa and 100 MPa at 50°C, 300°C and 400°C, respectively.

Current plans call for the first prototype blade to be fabricated from an austenitic stainless steel base plate (most likely a Type A-242 Nitronic alloy) which has high strength to resist the imposed forces and a low electrical conductivity which minimizes electromagnetically induced forces. To enhance heat transfer capabilities at the limiter surface, the cover plate will be fabricated from annealed OFHC copper or from a dispersion strengthened copper such as Glidcop A1-20 (C 15710).

As shown in Table 1, materials considered for use with the limiter include several copper alloys and several austenitic stainless steels. Aluminum alloys have been excluded due to relatively low strength and joining difficulties. High strength, aerospace aluminum alloys (7000 series, for example) are inherently strong but are not easily joined and would very likely overage in service resulting in a significant loss in strength. Conventional high strength copper alloys, such as precipitation hardened copper-beryllium are also not reasonable alternatives since they, like the aluminum alloys, will overage and soften in joining or in service. The decision was also made to exclude other copper alloys such as MZC and AMZIRC due to overaging concerns. Molybdenum alloys, such as TZM, have also been suggested as cover plate materials. These alloys have been rejected because of poor thermal conductivity relative to copper, the thermal expansion mismatch with copper or stainless steel, and potential joining difficulties with stainless steel or copper.

For the cover plate material OFHC copper has the highest thermal conductivity, and could be easily formed over the base for joining. One possible shortcoming of this material is its low yield strength (approximately 70 MPa). If stress analyses and testing indicate a need for higher yield strength, OFHC copper will be replaced with the Al-20 material shown in Table 1. The Glidcop Al-20 is essentially OFHC copper containing a fine dispersoid of Al_2O_3 (Cu-0.20 wt% Al_2O_3). Dispersion strengthened coppers are thermally stable and hence will not degrade unless melting of the material permits the Al_2O_3 to aggregate. The yield strength of annealed Al-20 is approximately 380 MPa and remains unchanged after one hour at 300°C. Since this is a relatively new class of materials, availability in the required shape sizes and grades may be a problem.

Type 316 stainless steel has often been suggested for high strength fusion reactor applications such as the limiter base plate, but for the current application the Nitronic alloys such as Type A-242 were selected over Type 316 because they have higher strength, are easily joined, and are readily available.

Copper and austenitic stainless steel have similar coefficients of thermal expansion and are good candidates for joining. Possible joining techniques include furnace brazing and diffusion bonding. At this stage of limiter development the most attractive joining technique is brazing. The copper could be joined to the stainless steel with a conventional silver braze such as BAg-18 (Ag-10Sn-30Cu) at a temperature of

approximately 750°C. The BAg-18 can be used without a flux if a H₂ atmosphere is used in the brazing furnace.

B. Coatings

Limiter surfaces are major sources of plasma impurities in tokamaks. Because energy losses rapidly increase with atomic number, Z , of the impurity element, it is desirable to have very low- Z materials on plasma interactive surfaces. This section outlines preliminary materials and fabrication recommendations to apply a low- Z armor over the ALT-II limiter blade. Additional testing and evaluation will be required to determine the optimum material and fabrication process.

As described in the previous section, the heat transfer surfaces of ALT-II will be made of copper. Bare copper would satisfy all design requirements except impurity control, and the sole purpose of the armor is to provide a low- Z surface. Thus, only materials with atomic numbers lower than copper ($Z = 29$) were considered. A list of candidate materials, in approximate order of increasing average atomic number, is the following: Be, B, B₄C, BN, BeO, SiC, Si₃N₄, AlN, Al, TiB₂, TiC, VC, V, Cr, Ni.

To achieve both a low atomic number and a relatively high heat flux, the best materials are Be, BeO and SiC, followed by TiB₂, TiC, Al and VC. Although Be and BeO are attractive candidates for use in future tokamaks, concern over the toxicity of these materials currently prevents their use in TEXTOR.

Therefore SiC is the apparent material-of-choice for the ALT-II armor. A worst case estimate of the hydrogen sputtering of SiC indicates that a 1-4 mm thickness is required to last for 50 plasma-hours (36,000 TEXTOR pulses). Unfortunately, applying a millimeter thick layer of SiC (or any of the other candidate ceramics) to a highly curved surface is a formidable problem. Millimeter thick coatings of SiC, TiB₂, TiC, etc., on a copper substrate are well beyond the practical limits of existing coating technology. It might be possible to braze small ceramic tiles over the surface of the limiter blade, but this would involve a substantial development effort and considerable expense. In order to overcome these fabrication problems, a composite coating, consisting of SiC particles in an aluminum matrix is being investigated as a possible alternative to pure SiC.

Samples of SiC/Al composite coatings deposited on OFHC copper substrates have been prepared for testing in the Sandia Electron Beam Test Facility. These coatings were deposited by a low-pressure plasma spray (LPPS) process with mechanical mixtures of SiC and aluminum powders as the feed material. The SiC/Al mixture sprays well and the prospects for millimeter thick coatings look very good.

The LPPS process was selected because it can achieve very high deposition rates (up to 1 mm/min with some materials), and it produces coatings that have less porosity, better adherence and higher thermal conductivity than conventional plasma sprayed coatings. LPPS produces superior coatings because deposition occurs inside a large evacuated chamber instead

of an ambient pressure environment.

As shown in Figure 2, the ratio of SiC and Al powders in the feed material can be varied to produce a graded coating, with more ductile Al-rich material adjacent to the substrate and more refractory SiC-rich material at the outer surface. Also, because aluminum forms a low-melting eutectic with copper a diffusion barrier between the composite coating and the substrate will probably be necessary. An LPPS deposited layer of nickel is a promising candidate for this diffusion barrier and offers the possible added bonus of increasing adhesion of the SiC/Al coating to the substrate.

The major potential disadvantage of the SiC/Al composite is the low melting temperature (660°C) of the aluminum matrix. Computer simulations with a modified A*THERMAL code [4] for a limiter coated with pure aluminum indicate that a disruption of 100 J/cm² for a 1 ms duration could produce a 200 μm thick melt layer and vaporize an additional 0.1 μm. There is some evidence that SiC/Al may be less susceptible to disruption damage than pure aluminum but the composite material is very difficult to model and testing is needed. Should the test results indicate that aluminum is an unacceptable matrix metal, nickel and possibly vanadium or chromium are alternative candidates.

IV. Thermal-Hydraulic Analysis

In most proposed designs for fusion power reactors, limiters will be exposed to heat fluxes near and above 200 W/cm². One of the most efficient methods of transferring

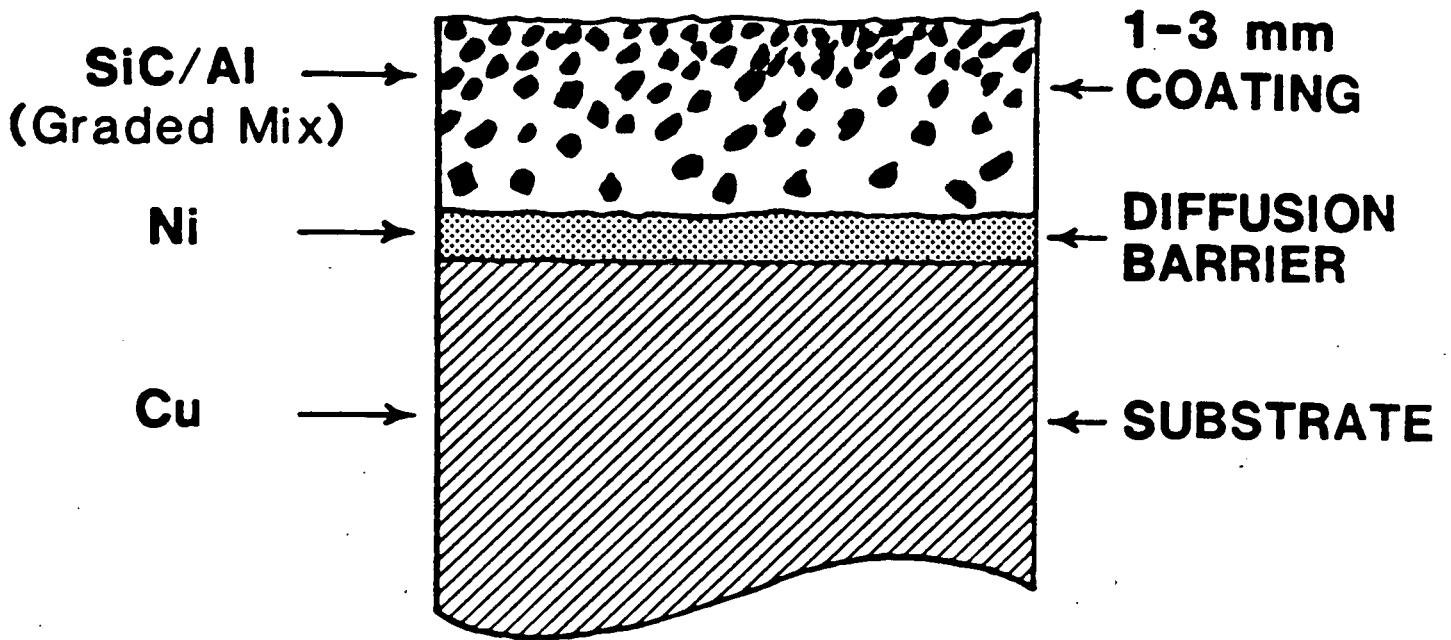


Figure 2. Graded SiC/Al armor coating. Low-pressure plasma sprayed coating is graded through depth so that high SiC content exists at surface, while high Al content exists near diffusion barrier.

large amounts of heat is via flow boiling. Relative to single phase convection, flow boiling can enhance the heat transfer by 200 to as much as 700 per cent. Among the many types of boiling processes, subcooled flow boiling is the most effective for accommodating the large heat fluxes which will be encountered on limiters and other fusion reactor components.

The thermal analysis of the preliminary design of the actively cooled ALT-II limiter consists of: (1) specification of the flow and flow coolant channel parameters to accommodate a peak heat flux of at least 200 W/cm^2 , (2) estimation of the associated pressure loss and critical heat flux (CHF), and (3) prediction of the temperature distribution around a typical coolant channel. Preliminary calculations, which will be discussed separately in an ALT-II feasibility study report, confirm that these criteria can be met with the use of subcooled flow boiling of water in channels with diameters in the range of 0.5 to 1.0 cm.

An additional specification is that of channel flow cross-section. Since sharp corners will generally enhance the onset of CHF [5], the boundary of the flow channel closest to the imposed heat flux boundary should be curved, not simply straight with rounded corners. The opposite boundary can have almost any shape (e.g., flat, circular).

In order to estimate the temperatures surrounding a typical coolant channel an analytical model which includes combined mode transport (e.g., stratification or slugflow) was developed. Two-dimensional finite difference numerical models, which represent one flow channel surrounded by either all copper

(thermal conductivity = $350/\text{cm}^2$), or copper with a 0.7 cm thick stainless steel backing plate (on the side opposite to the exposed heat flux), were implemented with the SINDA [6] code. Typical results from the model are shown in Figure 3: At the lower half of the channel the heat transport from the walls to the fluid was assumed to be due to forced convection to a single phase liquid (water at 49°C). Above this half of the boundary, the transport was assumed to be due to combined forced convection and subcooled boiling (i.e., subcooled flow boiling), and above the flow boiling region the heat transport was assumed to be due to convection to a single phase gas (at 200°C). Since it is not clear without more detailed study to what extent the upper part of the channel is occupied by vapor, the angle, θ (as measured from the center of the channel), which encompasses the vapor, was varied ($\theta = 36^\circ, 72^\circ$ and 108°). The heat transfer coefficient for the single phase regions was computed assuming the Dittus-Boelter [7] correlation for fully developed turbulent flow, while the coefficient for the flow boiling region was computed with Gambill's correlation [8].

V. Eddy Current Analysis

During a plasma disruption, the collapsing poloidal magnetic field induces eddy currents in the limiter, vacuum vessel, and other electrically conducting components. These eddy currents then interact with the strong toroidal and other magnetic fields to cause forces on the components.

To analyze the electromagnetically induced forces for ALT-II, the Princeton SPARK computer code [9] was used. The

SURFACE HEAT FLUX = 400 W/cm²

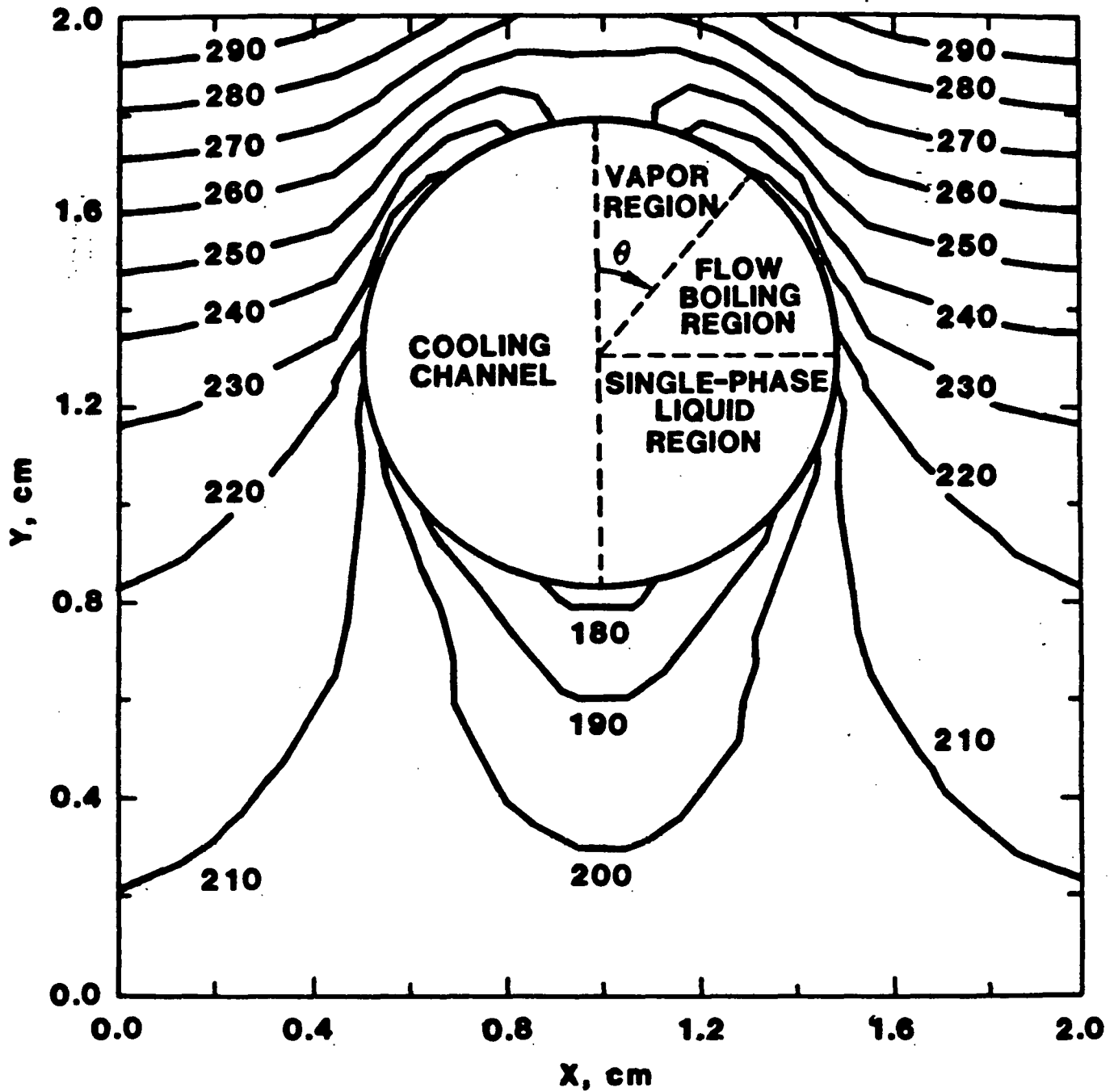


Figure 3. Temperature distribution for portion of limiter blade cross section. Temperatures shown are in °C for case with 400 W/cm² incident on top surface of limiter; all other surfaces are assumed adiabatic. Stratified flow model described in text is assumed with an angle θ of 36°.

code permits modeling the limiter and vacuum vessel as a three-dimensional arrangement of plates. The code output includes the forces at corner node points of each plate element.

A typical eddy current distribution for a plate model representing a 45° segment of a 30 cm wide limiter blade is shown in Figure 4. The off-center nature of the currents is caused by a bellows section of the vacuum vessel which lies directly behind the center of the eddy-current distribution.

VI. Structural Analysis

The total stress state in the limiter blade is produced by a combination of three generic types of loads: (1) mechanical, (2) thermal, and (3) electromagnetic. Design standards require that these stresses are kept below appropriate safety limits in order to prevent structural failure such as leakage of the coolant into the vacuum chamber or excessive structural deformation. Due to the preliminary nature of this study, the approach taken was to, first, identify which category of loads cause the highest stresses and, then, investigate different design options that would minimize those stresses. Both analytic and two-dimensional finite element models of the actively cooled substrate were used. Stresses in the low-Z coating are not addressed in this paper.

Mechanical loads include two types: (1) dead weight (e.g., gravity) and (2) coolant pressure. With a 30 cm wide, 45° toroidal segment, the dead weight load is approximately 600 N and can be easily accommodated by the limiter support structure. The other load, a water pressure of 1.5 MPa,

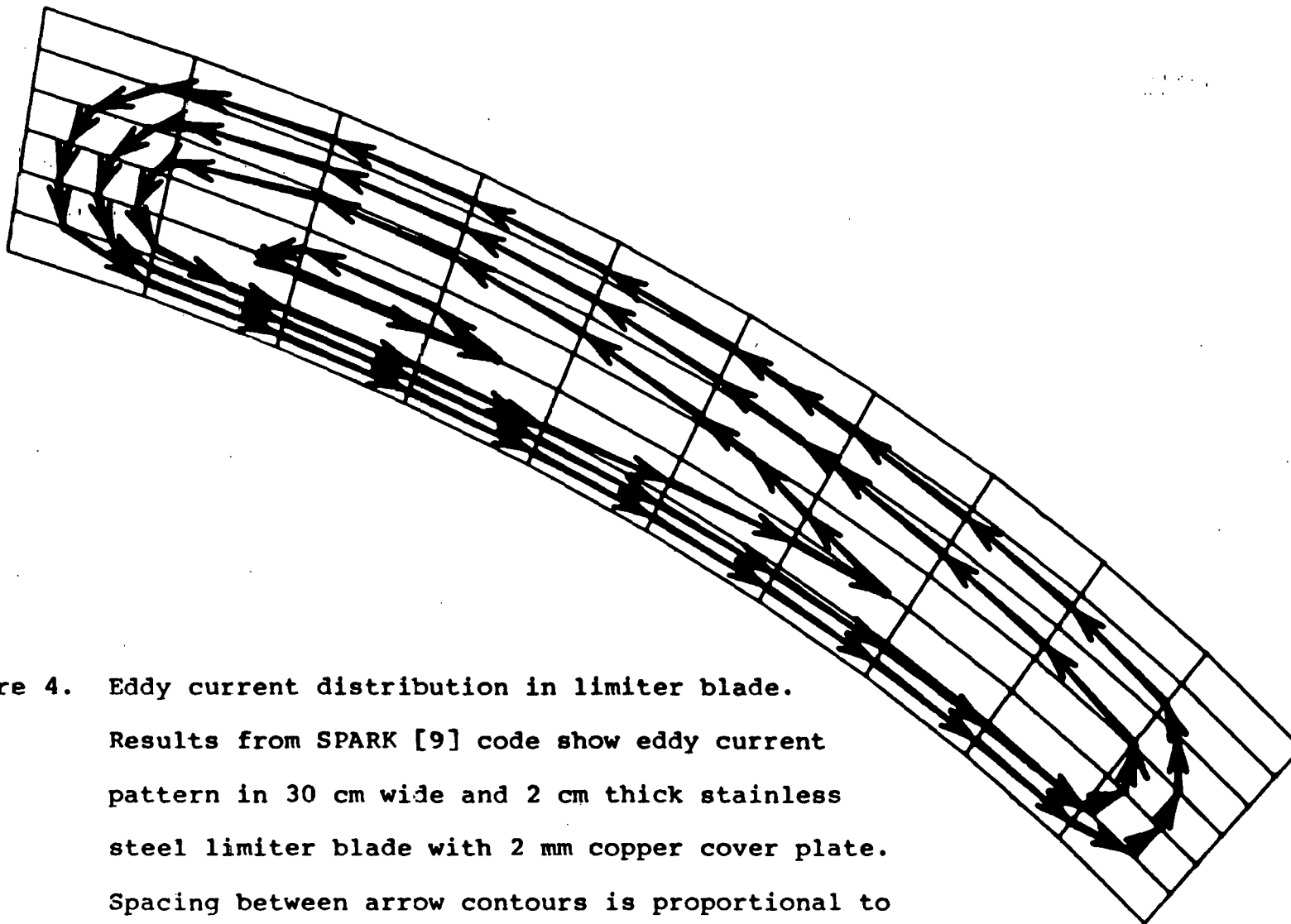


Figure 4. Eddy current distribution in limiter blade. Results from SPARK [9] code show eddy current pattern in 30 cm wide and 2 cm thick stainless steel limiter blade with 2 mm copper cover plate. Spacing between arrow contours is proportional to current density. Starting from inside, each row of arrows represents an approximate 1.6 kA increase in current.

causes bending stresses in a 2mm thick copper cover plate. With a spacing between channel ribs of 10 mm, the maximum bending stress is 20 MPa, considerably lower than the elevated temperature yield strength of the candidate copper alloys, typically 300 MPa (see Table 1). This pressure also causes tensile stresses at the braze joint between the copper channel ribs and the steel base plate. With a 5 mm wide rib, this stress is very low, 3 MPa.

For this analysis, a steady-state temperature profile is assumed through the cross-section of the limiter blade, as shown in Figure 3. Thermal stresses are primarily caused by the non-linearity of the temperature profile in this design. The temperature gradient through the thickness induces compressive stresses in the cover plate of -80 MPa and bending stresses in the base plate of 70 MPa. The ribs have bending stresses of 60 MPa. The maximum stresses occur at the sides of a limiter blade cross section where thermal deflection is largest, approximately 1 mm. Since the shear stresses at the braze location are significant, 10 MPa, the decision was made to groove thin channels into the base plate and lock the ribs into them, thereby keying the ribs against any sideways movement. Fabrication will be easier as well.

Reducing the thermal stresses can be accomplished in a number of ways. Choosing a thinner cover plate reduces the temperature difference across the plate. However, the plate cannot be less than 0.5 mm because bending stresses from the coolant pressure would eventually become too large. The

stress induced by the temperature difference between the cover and base plates could also be reduced by reducing the overall stiffness of the blade. This could be done by (1) reducing the distance between the two plates, (2) choosing a thinner base plate, or, (3) increasing the coolant heat transfer coefficient. The first two options also improve the particle pumping efficiency because the deflector plates are located closer to the plasma edge. Minimizing the thicknesses also minimizes the forces from eddy currents induced in a disruption. However, one drawback of having a thinner blade is larger thermal deflections or bowing, which may change both the heat flux profile and the particle collection rates.

Since the constraint of the hot cover plate by the cold base plate induces the largest stresses, one option is to heat the backside of the limiter so that both top and bottom thermally expand the same amount. For stainless steel, with a thermal conductivity twenty times lower than copper, a simple calculation shows that only 10 - 20 W/cm² at the backside is required to substantially reduce the front-to-back temperature difference.

As shown earlier in Figure 4, the dominant eddy current pattern is a rectangular loop in the plane of the blade. Only those components of the current that travel in a direction perpendicular to the toroidal field lines will produce significant forces from the vector cross product of the eddy currents and the magnetic field. Therefore, the resultant forces are concentrated at the blade ends and point perpendicular to the plane of the blade, towards the plasma at one end and

away at the other. For a 30 cm wide, 45° toroidal segment, the SPARK code predicts maximum forces of 3700 N at the end nearest the bellows section and -1990 N at the other end. These forces are time-dependent and peak at the end of the assumed plasma current decay at 10 ms. The stresses caused by these forces have not yet been calculated because they depend on how the limiter is supported. The best support location would be at the four corners where the forces would act directly on the supports.

VII. Conclusions

Promising candidates for limiter blade design and materials have been selected for ALT-II. Screening and analysis have led to an actively cooled limiter blade consisting of a copper cover plate over an austenitic stainless steel base plate. The copper cover of Glidcop A1-20 or OFHC copper provides good heat transfer characteristics, while a Nitronic type A-242 stainless base plate provides high strength with lower electrical conductivity to resist electromagnetically induced forces. A low pressure plasma sprayed graded coating of SiC in an Al matrix promises to provide an easily applied, thick (approximately 1 to 3 mm) armor for the limiter blade, but the coating is subject to further experiments to insure feasibility of application, and to evaluate the properties of the resulting coating.

Heat transfer analyses indicate that, for the anticipated surface heat flux of less than 200 W/cm², subcooled flow boiling in channels with a hydraulic diameter of 1 cm or less will adequately cool the limiter. Channel shaping to avoid

sharp corners is recommended to extend the subcooled flow boiling regime and avoid critical heat flux phenomena.

Stress analyses of the limiter head indicate that the greatest stresses arise due to the temperature gradient through the limiter body. To minimize these stresses, strategies to control the temperature gradients in the limiter are under investigation, including the possibility of controlling the heat flux to the stainless steel rear portion of the limiter blade which faces away from the plasma.

Acknowledgements

The authors would like to thank Dennis Croessman for his calculations with the A*THERMAL code. The authors would also like to thank Betty Brake for calculating the two-dimensional temperature profiles and Dr. R. T. McGrath at Pennsylvania State University for his sputtering calculations.

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