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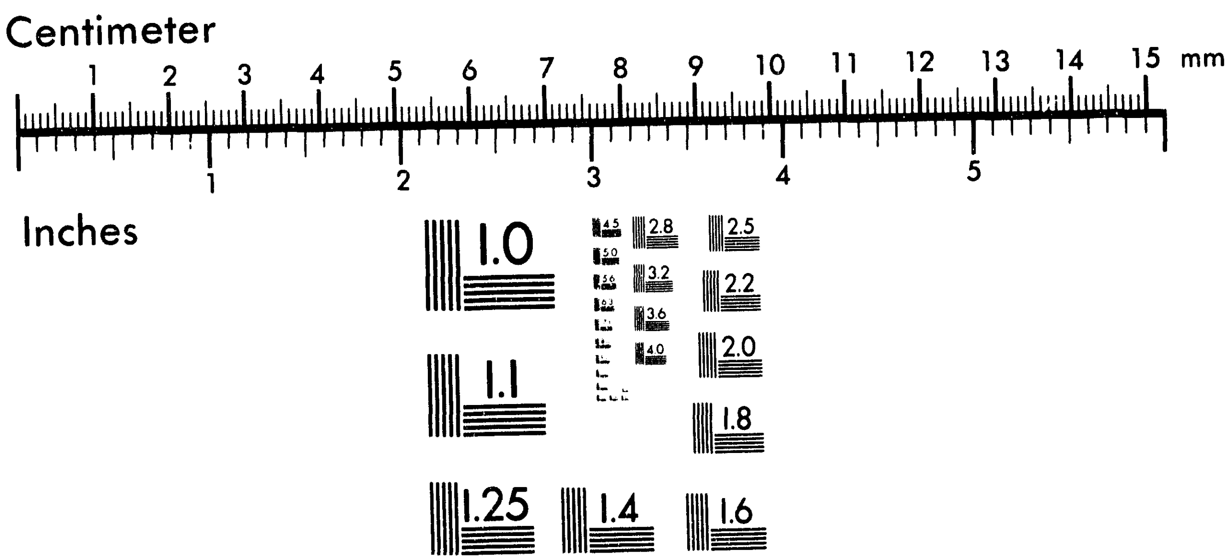

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ARIES TOKAMAK REACTOR STUDY

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DOUBLE NULL POLOIDAL DIVERTOR ANALYSIS FOR THE ARIES -2/4 REACTOR DESIGNS

1. INTRODUCTION

This report examines the feasibility of a standard poloidal divertor design for ARIES- 2/4 with the determination of the peak thermal loading on, and the plasma temperature facing a poloidal double null divertor. The ARIES-2/4 reactors produce 2,141 MW of fusion power of which 1712 MW is contained in the neutron channel. Of the remaining 429 MW of charged particle power, 47 MW is radiated from the core by bremsstrahlung and syncrotron modes to the vessel walls. The remaining 382 MW of charged particle or transport power crosses the core/edge interface. The fact that the bulk of the power is contained in the neutron channel makes the application of a poloidal divertor possible. The ARIES-2/4 divertor constraints for peak heat load (~5 MW/m^2) and peak particle temperature (T_e/T_i~30/20 eV) are set by current technology and materials knowledge. Divertor geometry constraints are imposed by the plasma equilibrium and the ARIES-2/4 vacuum vessel.

The divertor heat load and plasma temperatures are determined from edge particle and energy balances. These balances are important characteristics of the plasma edge because the transport power from the plasma core must pass through the edge and be deposited on tokamak components. The Braams' B2 code [1] is a multifluid ion and electron energy and momentum transport code for the plasma edge and is adopted for the design of the ARIES-2/4 divertor.

2. MODELING

The ARIES-2/4 divertor design relies on the formation of a cool, dense plasma adjacent to the divertor plate. High plasma density at the plate reduces the average particle temperature and flattens the energy flux profile. This situation corresponds to the experimentally observed high recycle mode of divertor operation [2]. This mode of operation can be simulated with the B2 code with an appropriate choice of boundary conditions. The B2 code allows for three types of boundary conditions for energy and ion continuity: particle density and temperature, particle and energy fluxes or a relationship between flux and density or flux and temperature. Boundary conditions for four of the six B2 boundaries - the wall, midplane, the cut through the X-point, and the private region boundary - are easily defined. If it is assumed that there is no net flux of particles or energy between adjacent divertor regions, then reflection at both the midplane, the cut through the X-point and the private flux boundary is required. Typical sheath conditions are required at the divertor plate and the conditions at the wall are set to maximize power on the plate. This leaves six undefined parameters at the core/edge interface Γ_p^i, n_i, Γ_E^{ie}, and $T_{i,e}$. For a well-posed B2 model it is necessary to stipulate three of the six available interface parameters as boundary conditions. Power production and plasma geometry are defined for ARIES-2/4. Therefore, stipulation the ion and electron power fluxes, Γ_E^{ie} is the appropriate core/edge energy boundary condition.

With the aforementioned particle reflection boundary conditions imposed on the B2 model, a net current of ions can only cross either the core/edge interface or the divertor plate. Assuming complete ionization of plate neutrals, the B2 edge particle balance can be easily written:

$$\int_{\text{plate}} \Gamma p(r,z)\,[1 - Rp(r,z)]\, d\sigma = \int_{\text{separatrix}} \Gamma s(r,z)\, d\sigma. \tag{1}$$

with suitably defined averages

$$\overline{\Gamma}_p A_p (1 - \overline{R}_p) = \overline{\Gamma}_s A_s\,. \tag{2}$$

where subscripts denote the divertor plate or the seperatrix.

With density conditions chosen at the core/edge interface, the plate recycle coefficient has little effect on the particle balance since the net particle flow across the core/edge interface can approach zero as the recycle coefficient goes to unity. However, choosing particle flux as the boundary condition we see that

$$\overline{\Gamma}_p = \frac{A_s\, \overline{\Gamma}_s}{A_p\,(1 - \overline{R}_p)} \tag{3}$$

and since the edge particle flux, $\overline{\Gamma}_s$ is a defined and positive value, the plate flux, $\overline{\Gamma}_p$ and therefore the plate neutral density must increase without bound as the recycle coefficient approaches unity. Increasing the particle flux to the plate reduces the average particle energy. The greatest increase in the position-dependent particle flux, $\overline{\Gamma}_p(r,z)$ and therefore, the greatest energy reduction per particle, occurs where the particle flux is greatest. This location approximately coincides with the peak of the divertor plate power flux profile. Therefore, the power flux profile tends to flatten during high-recycle operation.

The recycle coefficient, R_p within B2 is defined as the ratio of the integrated ion flux to, and the integrated neutral flux from the plasma side of the plate. This coefficient quickly reaches a constant value, near unity, during steady state or long pulse tokamak operation [3,4,5]. An excessively high recycle coefficient will raise the plate density to the point that particles diffuse back toward the core plasma creating unacceptable hollow profiles. This is avoided by comparing the edge density calculated by the B2 code and that specified in the systems code. ARIES-2/4 allows for a edge density equal to 70% of the average core density (1.99×10^{20} # /m^3). If the B2 edge density is greater than this limit (1.40×10^{20} # /m^3), the effective recycle coefficient must be reduced. An additional constraint may be the radiation caused by high-recycle operation which if too great causes the divertor plasma to cool and detach from the plate.

Within the B2 code, two dimensional orthogonal curvilinear coordinates account for the appropriate magnetic topology of the X-point within the poloidal plane. Currently the orthogonal coordinate system mandates that within the B2 model the divertor plate must be orthogonal to the magnetic field lines. This conflicts with the need to minimize the energy flux to the plate, which suggests a shallow angle of incidence thereby increasing plate area and reducing the energy flux.

Plasma asymmetries resulting from the Shafranov shift, and control fluctuations affect the energy deposited on the divertor plates. A Shafranov shift resulting in a 1:2, inboard:outboard power asymmetry, has been assumed for modeling the ARIES-2/4 divertor. This coincides with a ~2:1, inboard:outboard variation in divertor plate area. The factors of 1/2 and 2 cancel and the average energy fluxes to the inboard and outboard plates are equal. If it is further assumed that the plasma particles transported to the inboard and outboard edge regions have the same split as the energy, 1:2, we may then treat the two regions as the same, viz. the resulting particle density and particle and energy fluxes at the inboard and outboard plates will be equal. Therefore only the outboard side of the ARIES-2/4 divertor has been modeled with B2. Up-down asymmetries due to vertical control fluctuations or particle drifts have not been examined in this analysis.

3. RESULTS

The Braams' B2 code uses a fluid approach to model the edge region. Hydrodynamics equations with anomalous, diffusive, crossfield transport are employed. General orthogonal curvilinear coordinates are used to finite difference the equations. This allows the use of a conformal map to approximate the plasma equilibrium and generate the grid structure. As previously noted this orthogonal system conflicts with the desire to minimize the plate heat flux, accordingly the ARIES-2/4 divertor plate is inclined to an angle of 10° at the strike-point. For the actual design the plate is curved to maintain a constant divertor surface temperature outboard of the strike-point. Here however all B2 results are reported for a divertor plate with *every* magnetic field line incident on the plate at an angle of 10°.

Plasma particles radiate energy in the edge region. The B2 code contains a radiation model which approximates this energy loss. However B2 does not track this radiated energy since it is lost from the plasma fluid. Up to half of the energy radiated by plasma particles strikes the plate due to a maximum view angle of 2π steradians. This radiated plasma particle energy which strikes the plate is not distributed uniformly. In this analysis the radiated energy distribution is weighted by the plasma flux to the plate.

Throughout this entire analysis the results of individual runs varied regularly without erratic behavior and convergence was robust. A series of B2 code runs varying only the divertor plate recycle coefficient with a reduction of 20% in seperatrix transport power is presented here. This 20% reduction is the power loss from impurities not accounted for by B2. Increasing the recycle coefficient converts transport power to radiated power and broadens the total power flux profile at the plate. This is accomplished by increasing the neutral and plasma densities near the plate thereby increasing the rate of neutral/plasma interactions. Figure 1 shows the effect of increasing recycle coefficient on the total B2 power flux profile to the plate. This total B2 power is the transport power in the edge minus 50% of the power radiated by impurities. Core radiation which may strike the plate is excluded from these curves. The transport power for these curves is the design value of 382 MW. It is apparent from Figure 1 that the expected effects of high-recycle tokamak operation can be produced with the B2 code by varying the recycle coefficient with the appropriate set of boundary conditions. The important conclusion for ARIES-2/4 is that high-recycle operation allows for the use of a standard double-null poloidal divertor.

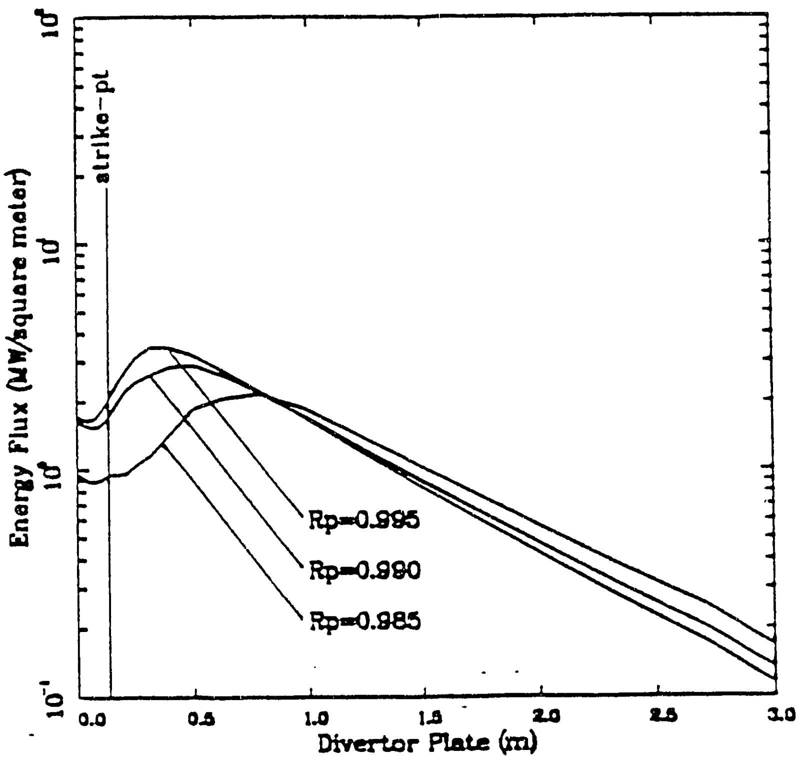

Figure 1 Recycle coefficient dependent total B2 energy flux to the ARIES-2/4 divertor plate, inclined at 10° and including 50% impurity radiation.

Figure 1 shows that the engineering constraint for peak heat flux ~5 MW/m^2 is achievable for all of the values of the divertor plate recycle coefficient examined in this analysis. However two additional constraints, the plate ion temperature limit (T_e~30 eV) and the seperatrix density (n_i^{sep} = 1.40×10^{20} # /m^3) restrict the operating recycle coefficient. Table 1 shows additional B2 results for the three cases presented in Figure 1. In the table, the electron temperature of Case 1 (R_p = 0.985) exceeds the target value of 30 eV and the seperatrix density of Case 3 (R_p = 0.995) exceeds the systems code edge density of 1.40×10^{20} # $/m^3$. Case 2 (R_p = 0.990) achieves all design criteria for the ARIES-2/4 divertor. Therefore, a double null poloidal divertor is a feasible solution for ARIES-2/4 heat and ash exhaust. The total B2 energy curve in Figure 1 with R_p = 0.990 is the ARIES-2/4 design case.

Table 1
PEAK DESIGN OF THE ARIES-2/4 DIVERTOR

	Case 1	Case 2	Case 3
Plate Recycle Coefficient	0.985	0.990	0.995
Total B2 Energy Flux MW/m^2	3.49	2.88	2.16
B2 Ion Energy Flux MW/m^2	1.61	1.45	1.14
B2 Electron Energy Flux MW/m^2	2.24	1.67	1.14
Electron Temperature eV	36.7	25.6	17.7
Ion Temperature eV	16.3	15.6	14.4
Seperatrix Density $10^{20}/m^3$	1.21	1.43	1.54

The distribution of the total power flux in Figure 1 for the design case of R_p = 0.990 between electron, ion, and recombination radiation channels is shown in Figure 2. Design curves for the plate plasma temperatures, density, and ion flux are seen in Figures 3 and 4, respectively.

The results of the B2 code for the ARIES-2/4 divertor design are presented in Table 2. the peak values for power flux and particle temperatures are within engineering constraints. The edge power balance shows the disposition of the 382 MW of transport power crossing the core/edge interface and the resulting average divertor plate energy flux.

The amount of transport power to one ARIES-2/4 outboard divertor incorporating a 2:1 outboard:inboard power asymmetry is

$$382 \text{ MW} \times \frac{1}{2} \times \frac{2}{3} = 127 \text{ MW} . \qquad (4)$$

Fifty percent of the impurity and plasma particle radiation appears at the vessel walls and does not reach the plate. This radiated power is, respectively, 25 MW and 10 MW. It is assumed that 10 W of transport power will reach the first wall. Thus, the power striking the one outboard divertor plate is reduced to 82 MW. The area of one outboard plate is ~ 36 m^2. The resulting average divertor plate energy flux is

$$\overline{\Gamma}_E^{div} = \frac{82 \text{ MW}}{36(m^2)} = 2.3 \text{ MW}/m^2 \qquad (5)$$

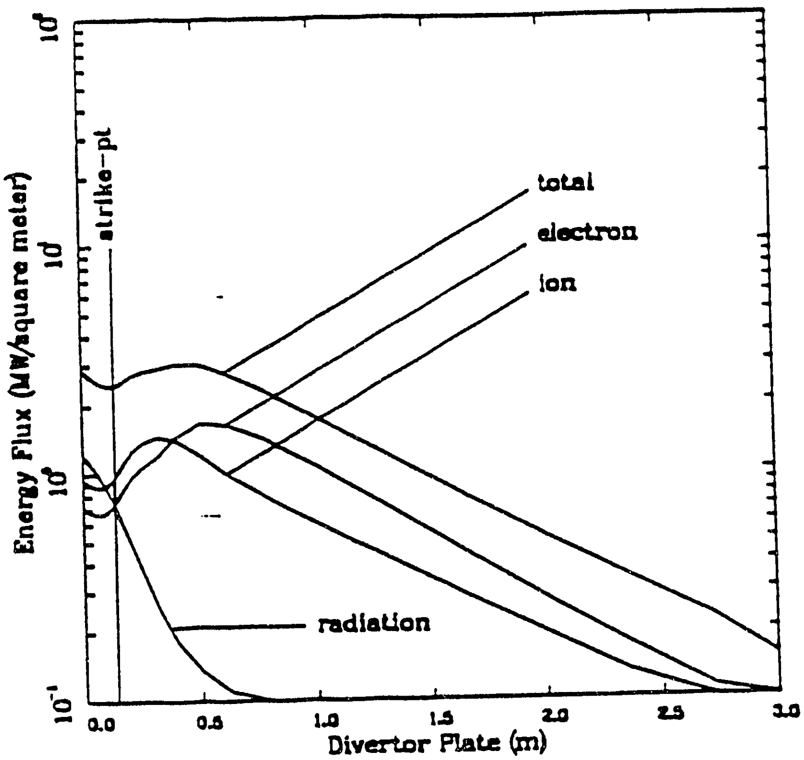

Figure 2. The distribution of the total B2 energy flux to the divertor plate. The radiation channel is plasma particle radiation.

4. CONCLUSION

The peak heat flux and particle temperatures are critical for the design of all tokamak heat control mechanisms. Both must be sustainable during steady-state operation without uncontrolled damage to the plasma facing components. During the ten years since STARFIRE [6], the target values for these critical parameters, energy flux (~5 MW/m^2) and temperature (T_e/T_i ~30/20 eV) and their means of attainment have remained unchanged. This is due to the materials of construction and the few options available for the task. It is desired that the divertor plate power flux be flat, thereby maximizing the total energy absorbed by the device and minimizing the need for transport power radiation. This flattening is accomplished in STARFIRE and TITAN I [7], with target shaping. ARIES-2/4 utilizes high recycle operation. The ITER [8], design incorporates the most conservative design philosophy of the four and therefore predicts the most peaked, albeit acceptable profile. When comparing the average and peak flux values for ARIES-2/4 and ITER it must be observed that the ARIES-2/4 edge density, 1.4×10^{20} # $/m^3$ is greater than that of ITER 3.2×19^{19} # $/m^3$. The higher edge

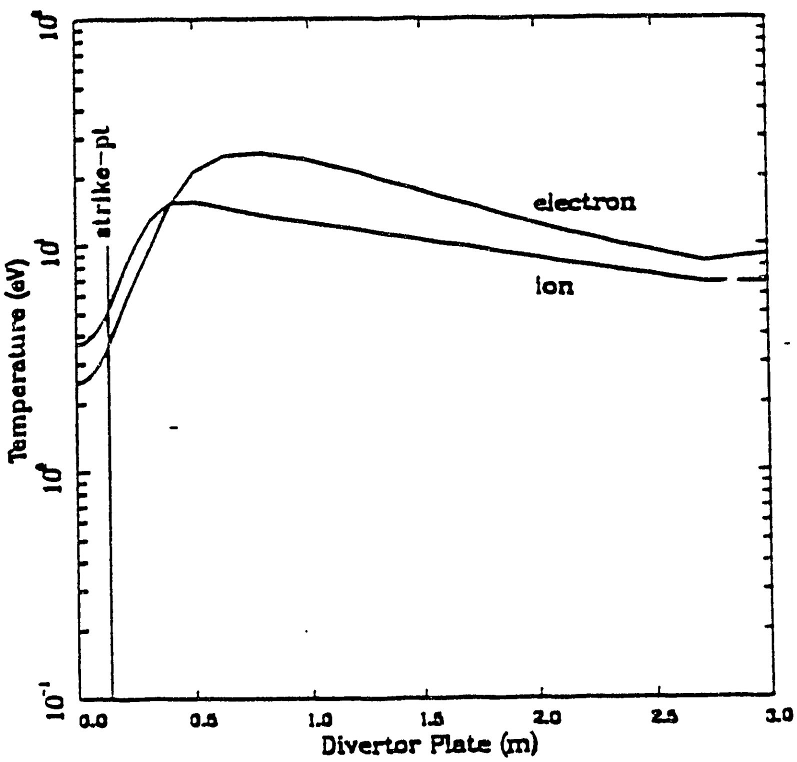

Figure 3. Electron and ion temperatures at the ARIES-2/4 divertor plate

density allows a higher recycle coefficient and flatter profiles. The temperature-dependent sputtering coefficient exhibits threshold and maximum values. STARFIRE attempts to operate at average temperatures sufficiently *above* the maximum value (> 200 eV), where sputtering coefficients are again acceptable. More reasonably, the three later devices operate at temperatures below the maximum and attempt to operate below the threshold. Thereby eliminating the need to address particles in the low energy tail. This fact—the order of magnitude reduction in predicted facing-plasma temperatures—and the shift toward high recycle operation to flatten the flux demonstrates the advancement of edge models and experimental observations. The uncertainty in the amount of energy radiated from the edge demonstrates the continuing need for model advancement.

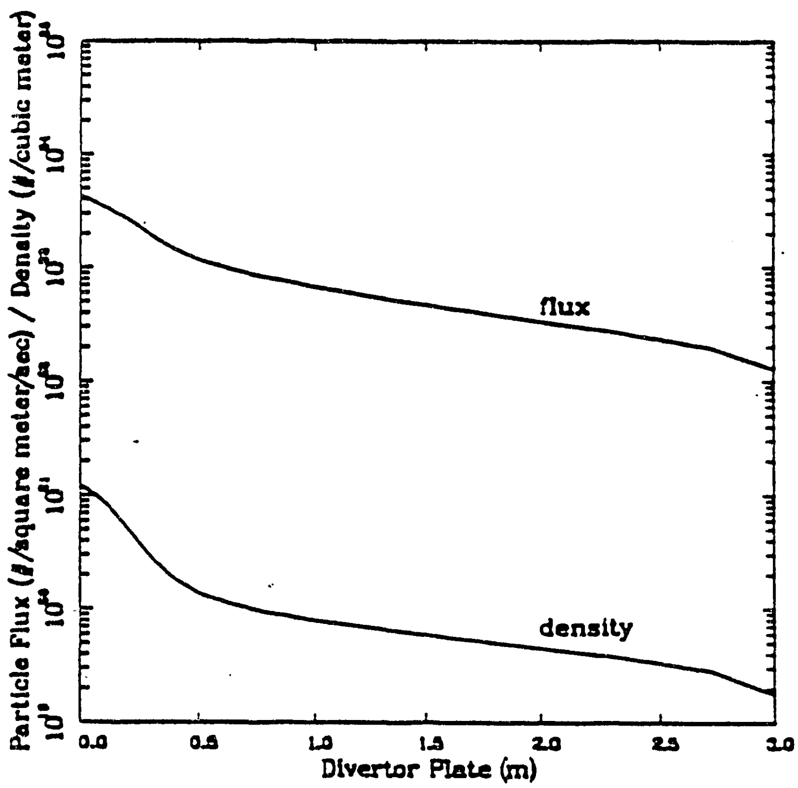

Figure 4. Ion particle flux and density at the ARIES-2/4 divertor plate

Table 2
ARIES-2/4 DIVERTOR PEAK OPERATING PARAMETERS

B2 Energy Flux MW/m^2	2.90
Electron Energy Flux MW/m^2	1.67
Ion Energy Flux MW/m^2	1.45
B2 Radiation Energy Flux MW/m^2	1.22
Electron Temperature eV	25.6
Ion Temperature eV	15.6

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