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A HIGH-RECYCLE DIVERTOR FOR ITER†

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ABSTRACT

A coupled one-dimensional (axial/radial) edge-plasma model (SOLAR) has been used to investigate tradeoffs between collector-plate and edge-plasma conditions in a double-null, open, high-recycle divertor (HRD) for a preliminary International Thermonuclear Experimental Reactor (ITER) design. A steady-state HRD produces an attractive high-density edge plasma ($5\times10^{19}m^{-3}$) with sufficiently low plasma temperature ($10\text{-}20\,eV$) at a tungsten plate that the sheath-accelerated ions are below sputtering threshold energies. Manageable plate heat fluxes ($3\text{-}6\,MW/m^2$) are achieved by positioning the plate poloidal cross section at a minimum angle of 15-30° with respect to flux surfaces.

I. INTRODUCTION

The primary function of a divertor is to isolate and protect the core plasma and physical walls by maintaining the heat and particle fluxes on material surfaces at manageable levels while preventing erosion products from entering the core plasma. Simultaneously helium generated during the DT fusion must be removed at a rate necessary to maintain acceptable core-plasma concentrations (< 5%). The high-recycle divertor (HRD) concept is envisaged to limit erosion by keeping the edge plasma electron temperature sufficiently low that the electric sheath-accelerated ion energy at the divertor plate is below sputtering thresholds. If the ion energy is too high, plate material will sputter until impurity line radiation lowers the temperature and sheath potential. This situation should be avoided so that impurities do not build-up and degrade (or quench) the core plasma.

A coupled one-dimensional (axial/radial) edge-plasma model (SOLAR) has been used to examine tradeoffs between collector-plate and edge-plasma conditions for the preliminary International Thermonuclear Experimental Reactor (ITER). The ITER parameters used here were for the US baseline (Generation 3)[1] which is a relatively small (major radius, $R_T = 4.04\,m$), low current (18 MA) design. Subsequent iterations by the international participants in the ITER design team have evolved the design towards a much larger ($R_T = 5.8\,m$) and higher current (25 MA) device which is not the subject of this paper. Generation 3 ITER parameters which are relevant to the edge-plasma characterizations are listed in Table I.

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TABLE 1. ITER GENERATION 3 PARAMETERS[1] AND ASSUMPTIONS FOR THE SOLAR MODEL

Plasma volume, V_p	$345\,m^3$
Separatrix area, A_p	$367\,m^2$
Major radius, R_T	$4.036\,m$
Minor radius, r_p	$1.410\,m$
Outboard SOL thickness, δ_{SOL}	$0.12\,m$
Power transported through separatrix,	
P_e	$38.2\,MW$
P_i	$34.4\,MW$
Core radiation fraction, f_{RAD}	0.2
Divertor heat and particle flux asymmetry factors:	
Upper-to-average, s_u	1.34
Outboard-to-average, s_o	1.19
Core-averaged ion density, n_c	$1.306\times10^{20}\,m^{-3}$
Energy confinement time, τ_E	$3.0\,s$
Outboard and upper separatrix fluxes: $\Gamma = n_c V_p s_u s_o/(4\tau_E A_p)$, $q = P s_u s_o/A$	
Particle flux, Γ	$1.6\times10^{19}\,m^{-2}s^{-1}$
Ion heat flux, q_i	$0.150\,mW/m^2$
Electron heat flux, q_e	$0.167\,mW/m^2$

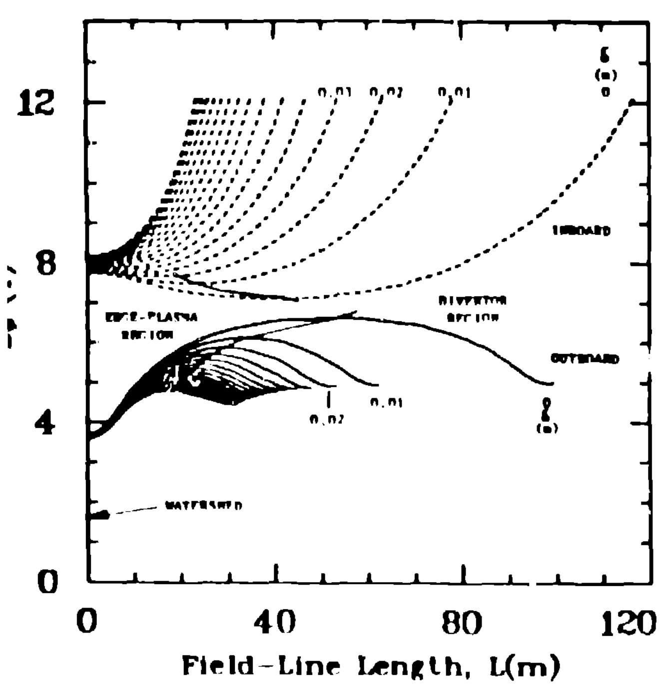
This paper concentrates on an open, double-null poloidal-field HRD with a tungsten divertor plate and a scrape-off layer (SOL) thickness between the separatrix and the first wall of $\delta_{SOL} = 0.12\,m$. An open divertor configuration, in which the plate is located adjacent to the core plasma, is used to minimize the space required by the divertor so that it can be located within the toroidal-field coils and capitalize on the flux surface expansion properties near the field null in order to reduce the peak heat flux on the plate. A double-null configuration is used primarily because it provides better stability properties for a highly elongated tokamak. This paper examines the outboard, upper divertor region with a tungsten divertor plate and a peak-to-average asymmetry factor of 1.5 assumed for the total power entering this divertor quadrant.

II. SOL PLASMA MODEL

The SOL plasma is comprised of the edge plasma which lies across the separatrix from, but next to the core plasma, and he divertor plasma which exists in the region between the ield null and the divertor plate. The SOLAR model treats he SOL plasma up to the plasma sheath, which exists within a few Debye lengths of the plate surface. The field-line connection length is defined as the half-length of a magnetic-ield line in the SOL between collector plates. Because plasma energy transport parallel to magnetic-field lines is much more rapid than cross-field transport, connection engths that are sufficiently long are desirable so that radial transport can diffuse the peak parallel heat and particle fluxes before these field-lines intercept a collector plate.

n order to provide the necessary resolution of the SOL geometry and the necessary data format for the SOLAR model, the Generation 3 magnetics geometry was reproduced using the NEQ equilibrium code[2] with Los Alamos modifications that calculate the SOL fields, flux surfaces, connection lengths and area expansion factors on n extended grid and at specified locations. Figure 1 contains a sample of these results, which are used by the parallel-transport model and plate locator model in SOLAR.

'he coupled-1-D approach of SOLAR is illustrated in Fig. . Since both parallel and radial transport is important, nd since both first wall and divertor plasma conditions are crucial to the design, the SOL is inherently a two-dimensional 2-D) problem. The coupled 1-D SOLAR model allows issues associated with both radial and poloidal variations



igure 1. Toroidal field versus field-line length for various eld lines in the SOL of the ITER Generation 3[1] (A089) magnetic configuration

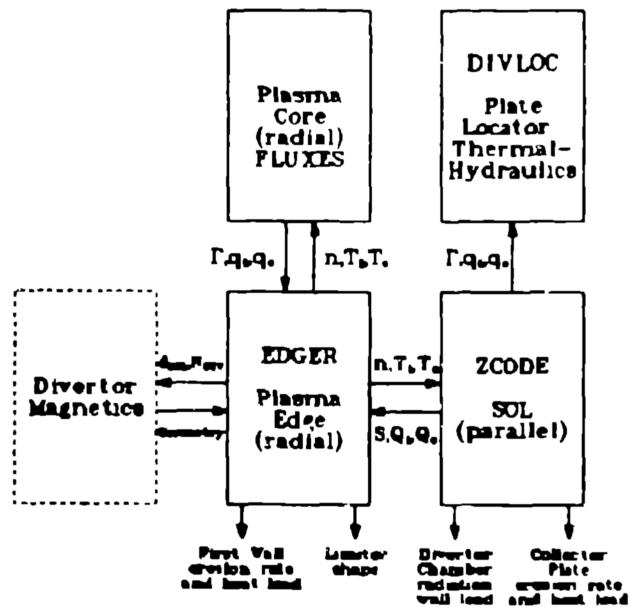
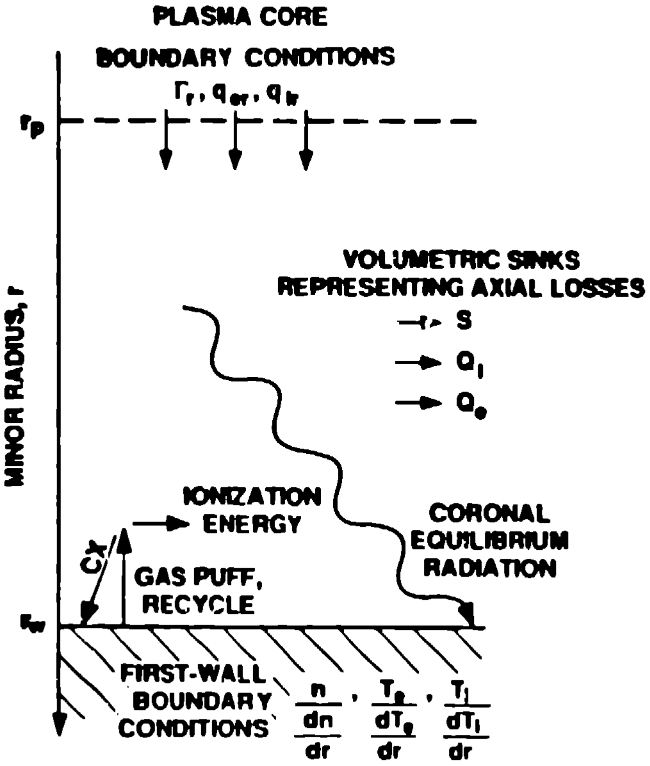


Figure 2. Logic diagram for the coupled 1-D SOLAR edge-plasma model.

to be addressed. Input requied by SOLAR includes the magnetic topology and the heat and particle fluxes across the separatrix. Neutral-atom transport effects occurring near the plate have been included only through an assumed plasma recycle coefficient. The remainder of this section describes the plasma models.

Edge Plasma. One of the main goals of the edge-plasma model is to calculate the peak loads and the plasma conditions at both the first wall and the collector plate. Peak heat fluxes on the first wall occur in the plasma edge at the outboard symmetry surface (i.e., "watershed" point) which is located midway between collector plates. A radial calculation, therefore, must link the plasma core to the first wall, r_w, along this symmetry surface. A code called EDGER was created to describe time-dependent, radial, two-fluid transport in the edge plasma. The model is based upon Braginskii,[3] except for the particle and thermal radial diffusivities which are assumed to scale like Bohm. Losses related to parallel transport appear as volumetric sink terms based upon simple analytic models assuming thermal conduction dominates energy losses, and some fraction of free streaming losses determine particle loss. Checks were added to ensure that thermal conduction losses do not exceed free-streaming limits. An energy flow diagram is contained in Fig. 3. This code can be extended into the core plasma, if necessary, to resolve steep gradients at the plasma radius of the core/edge interface, r_p. Important features include a 1-D neutral-atom transport model (SPUDNUT)[4] for a more accurate plasma source term, a Bohdansky[5] physical sputtering calculation, and a coronal equilibrium line radiation model with specified impurity concentrations



lgure 3. Energy flow diagram for the radial transport escription of the edge-plasma model of SOLAR.

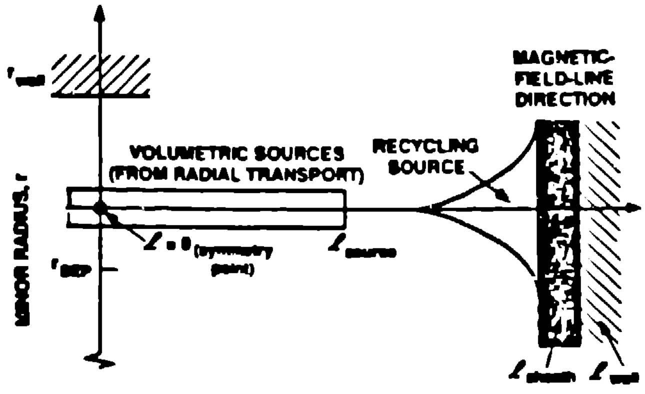


Figure 4. Energy flow diagram for parallel-field transport description of the SOL plasma transport model of SOLAR.

rallel Transport Model. The build-up of an electric sheath front of the collector plate and plasma recycle result strong variations of density and temperature profiles ong a field line in the SOL. A one-dimensional (1-D) rallel-field description, therefore, is necessary to calculate curately these variations and to resolve issues related to OL impurity radiation, wall loads, and impurity entrainment the divertor chamber. A parallel, two-fluid, steady-ate code, ZCODE, was developed to meet these needs in mbination and compatibility with the previously described dial plasma models.

he geometry of ZCODE is illustrated by Fig. 4. A eady-state description is sufficient because the parallel ansport reaches equilibrium on a much shorter time scale ian the radial diffusion time. Thermal conduction is cluded and uses classical parallel thermal conductivities, ith a free-streaming limit applied. Ion kinetic energy and omentum is included to account for the large acceleration y the plasma pre-sheath. Sheath boundary conditions e enforced in front of the collector plate, including sonic ow (i.e., Mach number, $M = 1$). The sheath ion and ectron energy transmission factors, γ_i and γ_e, are taken $\gamma_e = 2.9$, and $\gamma_i = 1.9 + 0.5\,T_e(\ell_c)/T_i(\ell_c)$, respectively. he cross-sectional area of a field line bundle is included model the expansion and contraction of field lines in e divertor. Volumetric source and sink terms include ectron-ion temperature equilibration, ionization, charge-exchange, radial transport effects, and impurity radiation. A SPUDNUT[4] calculation is used to benchmark the charge-exchange and ionization terms.

The impurity radiation model assumes a constant impurity fraction and coronal equilibrium. A time-dependent coronal radiation model is really required in the low temperature regime to estimate accurately radiation powers. In addition, coronal-equilibrium radiation data for high-Z impurities does not exist for temperatures below ~ 80 eV, and some extrapolation must be used. The line-radiation was assumed to extrapolate as $T_e^{\frac{1}{2}}$ from the lowest temperature data available to zero at 1 eV. The coronal equilibrium and the temperature extrapolation assumptions should underestimate radiation losses. The ZCODE model also includes physical sputtering calculations of the collector-plate material while accounting for the sheath acceleration of the ions.

Edge(Radial)/ZCODE(Parallel) Plasma Coupling. In order to obtain the peak heat fluxes and erosion rates at the first wall and collector plate, the radial and parallel edge-plasma computations must be coupled. The parallel transport calculation is performed on field lines located just outside of the core/edge interface, r_p, where the parallel heat flux is a maximum. The coupling process begins by first guessing the parallel-field loss terms and then estimating the edge-plasma conditions with the radial code. The resulting density and temperatures of the symmetry point at r_p are then fed to the parallel transport code, which solves for the parallel profiles. The resulting parallel heat and particle fluxes are converted into effective volumetric sinks and returned to the radial code to begin an iterative process. The parallel losses at other radial points are assumed to scale according to the analytic model described above. The iteration is repeated until the six continuity conditions converge. Since the edge plasma code is time-dependent, one iteration could be done at each time step. For steady-state solutions, the edge plasma code an be run to steady-state within each iteration. Typically, wo to four iterations between the EDGER code and SOL alculations are sufficient for convergence.

Divertor Plate Location. The computer code DIVLOC was written to calculate the normal energy flux on some pecified plate shape and location, or an optimum shape that ninimizes the flux subject to a minimum angle constraint etween the plate and the flux surfaces in a poloidal cross ection. The DIVLOC code utilizes the magnetic topology om NEQ and the parallel heat flux results of EDGER and CODE, as well as estimations of radiated powers. The plate also located at least several neutral-atom ionization mean ee paths away from the core plasma in order to isolate he core plasma from recycling at the plate. The DIVLOC ode also estimates thermal-hydraulic properties of the plate ased upon a 2-region slab model that includes a surface eat flux on the front face, forced convection cooling on the ackface, and volumetric neutron heating. Coolant pressure nd pressure drops, tube stresses, and critical heat flux are lso estimated.

Model Capabilities and Limitations. The complete plasma odel characterizes the temporal and spatial evolution f the plasma and calculates the peak heat flux and osion rate of the first wall and collector plate. This aracterization includes such physical effects as radial and arallel transport, radiation (coronal equilibrium), gas-puff efueling, 1-D neutral atom transport, and plasma sheath onstraints. Additional information provided by the models ncludes ion and neutral-atom physical sputtering rates, a heck for viscous entrainment of impurities in the divertor hamber, and divertor plate shape and location. Perhaps he most significant limitations of the model include: a) he model cannot predict potentially important 2-D neutral-tom transport effects, b) the impurity radiation model is ased on coronal equilibrium, and c) parallel solutions in the OL can be difficult to find.

II. RESULTS

nput assumptions that complete the SOLAR model are ummarized in Table II. At the time of this study, neutral ransport calculations had not been done for ITER; to void local flow reversal wherein plasma particles near the eparatrix flow from the divertor back into the edge plasma, he local plate recycle coefficient was chosen to be less than ne. Flow reversal is undesireable because it will aid the ransport of impurity ions into the core plasma. Recent alculations considering neutral-atom transport suggest that trong local flow reversal will occur. Strong local flow eversal has a negligible effect on both the energy flows in e SOL and the required upstream density at the separatrix, hich are the subject of this paper; however, significantly harpened density gradients between the separatrix and the rst wall can result

TABLE II. SOLAR MODEL INPUT ASSUMPTIONS

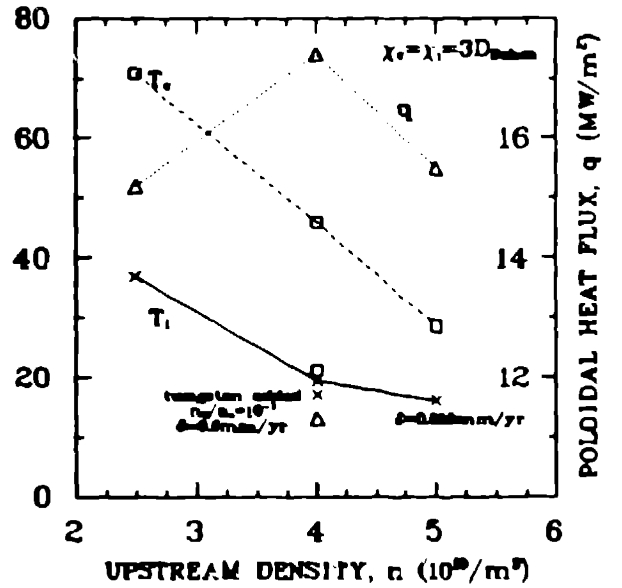
Particle diffusivity, D	D_{Bohm}
Ion thermal diffusivity, χ_i	$3 \times D$
Electron thermal diffusivity, χ_e	$3 \times D$
Plate recycle coefficient, R	0.99956
Energy consumed per ionization,	
w_i	$-5\,eV$
w_e	$20\,eV$
Field-line connection lengths:	
watershed-to-null, L_n	$25\,m$
watershed-to-plate,* L_p	$38\,m$
Field at plate,*	
B_θ	$0.22\,T$
B	$6.09\,T$
Neutral-hydrogen ionization mean free path at the plate, γ	$0.025\,m$
Effective ionization mean free path $\gamma_{eff} = \gamma B/B_\theta$	$0.69\,m$

* For the field line at $r_p + 0.01\,m$.

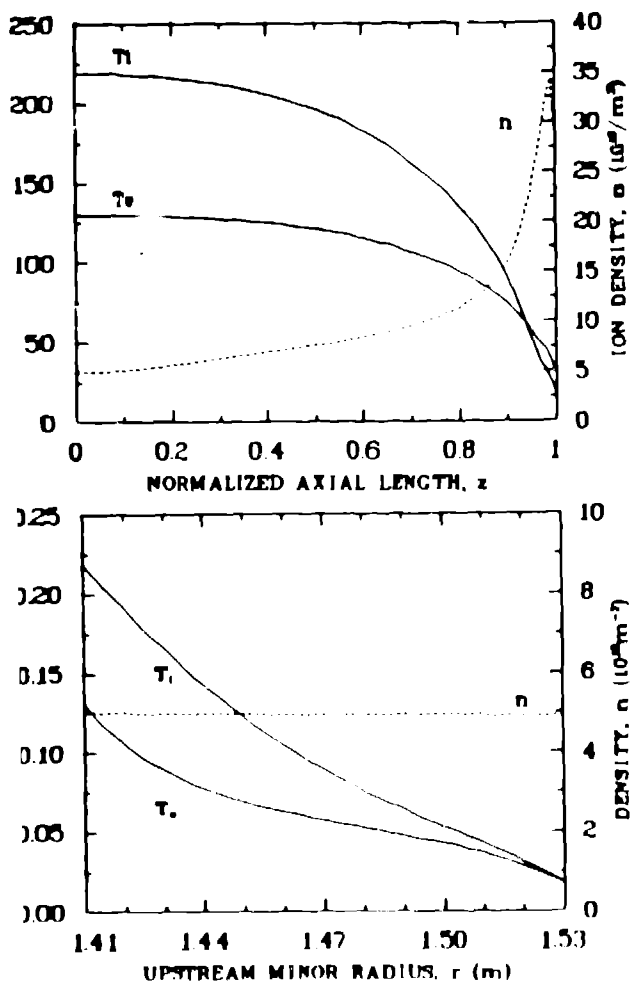
SOL Plasma Parameters. The goal of the present study was to identify plasma conditions that have sheath temperatures sufficiently low ($T_{e_s} + T_{i_s} \leq 45\,eV$) that plasma striking the plate will have energies below the sputtering threshold. The global plate recycling was varied until the upstream, separatrix density was sufficiently high ($5 \times 10^{19} m^{-3}$) to lower the temperatures to desired values. The dependence of sheath temperature on upstream density is illustrated in Fig. 5. The effect of impurity radiation is demonstrated by adding tungsten at a constant impurity fraction of 10^{-3}. For the resulting SOL radiation fraction of the required upstream density is reduced by 20%. The increased plate erosion rate from self-sputtering is still below the nominally acceptable value of 1 mm/yr. Such high concentrations of tungsten, however, could have negative effects on the core plasma and probably should be avoided.

SOL plasma axial and upstream radial profiles are presented in Fig. 6 and summarized in Table III. The resulting parallel heat and particle fluxes at the plate are given in Fig. 7. The upstream, parallel-heat-flux, radial e-folding distance is 15 mm.

Divertor Plate Configuration. The magnetic topology and the parallel heat flux at the sheath can be used for optimizing the plate shape as described in Sec. II. Three acceptable configurations from a heat flux point of view (~ 4-6 MW/m^2) are shown in Fig. 8 with normal heat flux values presented in Fig. 9. All three configurations have the plate intersecting the first field line at an angle of 15 degrees. The difference between configurations is only the sign of the angle and the starting point of the plate. Combinations of



...ure 5. Sheath temperatures and poloidal heat flux versus ...stream density.



...ure 6. Radial and axial SOL plasma temperature and ...sity profiles

TABLE III. SUMMARY OF SOL PLASMA

Sheath/Separatrix Conditions	
density, n	$28.6\times10^{19}\,m^{-3}$
ion temperature, T_i	$16.1\,eV$
electron temperature, T_e	$28.5\,eV$
parallel heat flux, q	$435\,MW/m^2$
parallel particle flux, Γ	$1.19\times10^{25}\,m^{-2}s^{-1}$
tungsten sputtering erosion rate, δ	$0.026\,mm/yr$
Upstream/Separatrix Conditions	
density, n	$5\times10^{19}\,m^{-3}$
ion temperature, T_i	$219\,eV$
electron temperature, T_e	$130\,eV$
Upstream/First-Wall Conditions	
density, n	$5\times10^{19}\,m^{-3}$
ion temperature, T_i	$17\,eV$
electron temperature, T_e	$16\,eV$
radial heat flux, q	$0.04\,MW/m^2$
radial particle flux, Γ	$1.\times10^{19}\,m^{-2}s^{-1}$

sections of the three plates are also acceptable provided all field lines intercept the plate. Considerations other than heat flux constraints, such as neutral-particle transport, vacuum pumping, plasma recycle, and plate maintenance and replacement, are required to choose a final design.

A rough estimate of the effect of equilibrium shifts on the heat flux is accomplished by shifting the plate ±0.1 m relative to a fixed equilibrium and very roughly about a 50% increase in the peak flux is obtained. It is noted that the divertor locator was applied to a plate shape suggested originally in Ref. 6 and found to be in excellent agreement with the estimated heat flux.

Density e-Folding and Helium Removal. A core plasma fuel burn-up rate of 0.005 and a maximum acceptable alpha-impurity fraction of 0.05 implies the alpha-particle confinement time, τ_α, to be $\gtrsim 10s$. Here, τ_α is defined by $n_c V_c/\tau_\alpha \equiv D_u n_u A_{sep}/\Delta$, where Δ is the density radial e-folding distance and the subscripts c and u refer to the core-average and the edge-upstream values.

The global plate recycle coefficient, R_p, is defined such that for every X plasma particle striking the plate, $R_p X$ are returned to the plasma, thus $\Gamma_s A_s = \Gamma_u A_u(1+R_p+R_p^2+R_p^3\ldots) = \Gamma_u A_u/(1-R_p)$. Using particle balance, Fick's Law with a diffusivity of $1m^2/s$, and a unity mach number at the sheath, Δ is found to be

$$\Delta^2(m) = 2.3\times10^{-4}L_u(m)\sqrt{T_e(eV)}/[T_u(eV)(1-R_p)].$$

Using $\tau_\alpha \leq 10\,s$, $L_m = 25\,m$, $T_e = 20\,eV$, $T_u = 80\,eV$, and $n_c/n_u = 1.7$ gives $R_p \geq 0.999992$. Such a global plate recycle coefficient constraint should be easily satisfied in a HRD.

By contrast, the constraint on core/edge recycling scales linearly with $(1-R_c)$ such that $R_c \geq 0.94$. Divertors that have plates located sufficiently far from the core plasma have

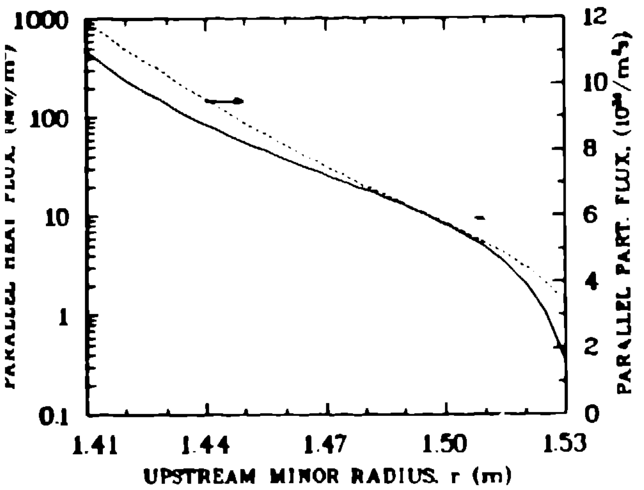


Figure 7. Parallel particle and energy heat flux *versus* upstream field line minor radius.

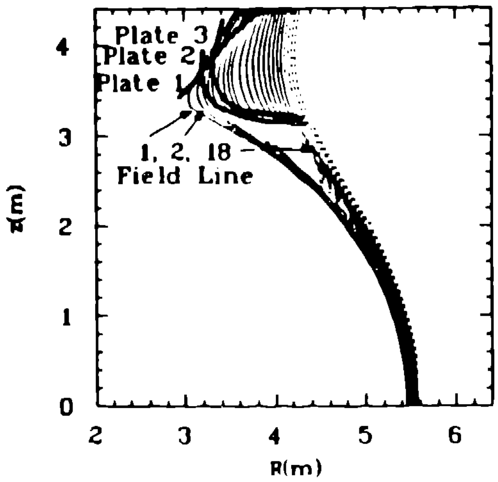


Figure 8. Three acceptable collector plate configurations from a heat flux viewpoint.

$_r \simeq 0$, so this constraint should also be satisfied. As long as alpha-particles diffuse similarly to the background plasma, helium removal should not be a problem.

V. SUMMARY

The present calculation for a steady-state ITER plasma suggests an HRD can achieve acceptable plate heat fluxes (3-4 MW/m^2 peak) at the collector plate with appropriate plate shaping. This design can also withstand toroidally symmetric plasma shifts of 0.1 m while maintaining the peak fluxes below ~ 7 MW/m^2. Toroidally asymmetric plasma shifts and rotations or plate misalignment have not been examined, but, because of the small angle between the field lines and the plate (1°), these shifts and misalignments potentially cause increased peaking.

Low erosion rates for tungsten divertor plates are computed provided the peak upstream edge-plasma density is sufficiently high ($\sim 5 \times 10^{19}/m^3$) to allow low sheath

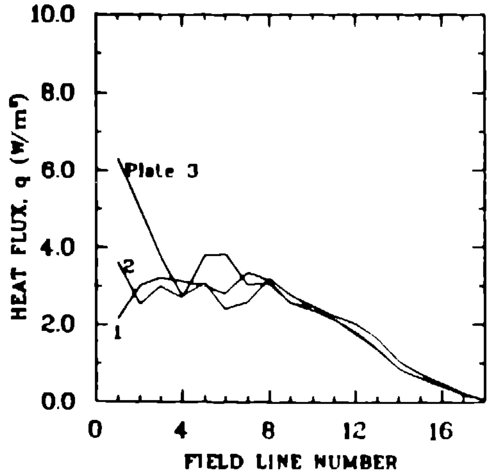


Figure 9. Normal heat flux *versus* field line number for the three plate configurations.

temperatures ($T_e + T_i \lesssim 45\, eV$). A high edge-plasma density at the wall results from an assumption of no flow reversal and is probably not correct for an HRD. Neutral-atom transport must be followed in two dimensions to describe correctly the particle flows.

The HRD appears to be compatible with helium-ash removal and in general should reduce the steady-state vacuum pumping requirements by allowing higher neutral-atom densities. The HRD also should protect the first wall from high-heat flux and erosion rates.

In conclusion, the HRD provides an attractive option for providing impurity/wall protection. An open-divertor configuration conserves valuable volume within the tokamak toroidal-field set. The divertor plate should be inclined in a poloidal cross section at the maximum angle ($\geq 15°$) with respect to flux surfaces that still reduces the heat flux to manageable levels (3-6 MW/m^2). The plate must be easily repaired and replaced. Toroidal asymmetries must be minimized. Finally, a tungsten surface provides the superior sputtering properties for steady-state operation, however, disruptions and other instability effects need to be considered in making the final choice of material.

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