CONF-760935-48

IMPURITY CONTROL IN NEAR-TERM TOKAMAK REACTORS

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Second ANS Topical Meeting on The Technology of
Controlled Nuclear Fusion
Richland, Washington
September 21-23, 1976

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Paper presented at *Second ANS Topical Meeting on The Technology of Controlled Nuclear Fusion*, September 21-23, 1976, Richland, Washington; and for publication in the *Proceedings*.

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CTR PROGRAM
Argonne National Laboratory
Argonne, Illinois 60439

October 1976

^{*} Work supported by the U. S. Energy Research and Development Administration.

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Weston M. Stacey, Jr., Dale L. Smith, and Jeffrey N. Brooks
ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS 60439

Several methods for reducing impurity contamination in near-term tokamak reactors by modifying the first-wall surface with a low-Z or low-sputter material are examined. A review of the sputtering data and an assessment of the technological feasibility of various wall modification schemes are presented. The power performance of a near-term tokamak reactor is simulated for various first-wall surface materials, with and without a divertor, in order to evaluate the likely effect of plasma contamination associated with these surface materials.

The problem of plasma contamination by wall-sputtered impurities in near-term tokamak reactors is examined. A critical review of the relevant surface data is incorporated in a plasma-wall interaction model that is employed, together with a plasma power and particle balance model, to evaluate impurity contamination effects. Impurity control by charged-particle diversion and by modification of the first-wall surface are considered, and the adequacy of these methods is assessed.

A major purpose of this work is to determine if modification of the first-wall surface can provide adequate impurity control for near-term tokamak reactors, in general, and the experimental power reactor (EPR), in particular. A qualitative assessment of the technological feasibility and limitations of a low-Z coating, a low-Z separated liner, a carbon curtain, and a low-sputter coating is presented.

It is concluded from these studies that adequate control of sputtered impurities to sustain burn pulses on the order of a minute and to achieve net power conditions can be

obtained in an EPR by suitable modification of the first-wall surface. Of the wall modifications considered, a low-Z material (e.g. beryllium) coated on a structural substrate appears the most technologically feasible.

COMPUTATIONAL MODEL

The basic computational model consists of a set of time-dependent, space-independent particle and power balance equations for the plasma, and a plasma-wall interaction model. Coupled balance equations for D-T ions, alpha particles, wall-sputtered impurities, electron temperature, and ion temperature are solved. Neutral beam and fusion-alpha heating and power loss by radiation and transport are treated. Transport processes within the plasma are modeled with particle and energy confinement parameters which are computed from a multiregime (pseudo-classical, neoclassical, trapped-particle-mode) model depending upon the value of the collision frequency.

The plasma-wall interaction model is depicted schematically in Fig. 1. Charged (D^+ , T^+ , He^{++} , impurity) and neutral (D^0 , T^0 , n) particle fluxes emerge from the plasma and strike the wall, with the charged particle fluxes being reduced by a factor n due

*Work supported by the U. S. Energy Research and Development Administration.

Definitions:

- +/- outward/inward particle flux.
- r_n^+ external neutral D-T source.
- A_{cx} charge-exchange re-emission probability.
- P wall reflection coefficient
- S wall sputtering coefficient.
- η charged particle removal efficiency.

FIGURE 1. Plasma-Wall Interaction Model

to particle removal (e.g. by a divertor). A fraction of these particles are reflected, predominantly as neutrals from the wall with reflection coefficient R .^{*} The impinging particles produce wall erosion by sputtering with coefficient S . The returning particles are either ionized in the plasma or may initiate a series of charge-exchange interactions leading to the re-emergence of a D^0 or T^0 from the plasma with a probability A_{cx} which depends upon the relative charge-exchange and ionization cross sections and

^{*} R includes backscattering and re-emission.

upon neutral transport.

Energy-dependent physical sputtering coefficients for the incident particles, viz., D^+ , T^+ , He^{++} , and impurity ions, on candidate first-wall materials are used for the calculation. Since insufficient experimental sputtering data are available for the range of parameters of interest (1-5 are general references that give a good indication of the state of technology), the sputtering coefficients used for the calculation have been developed from both theoretical and empirical considerations. The shapes of the energy-dependent sputtering curves are

developed primarily from Sigmund's theory⁽⁶⁾ and the magnitude of the coefficients have been adjusted in some cases to better conform with available experimental data.

Since the Sigmund theory does not adequately predict light ion sputtering at low energies, energy-dependent sputtering yield curves for light ions (deuterium, tritium, and helium) have been obtained by combining the theoretical curve at higher energies with an empirical relation for the lower ion energies.⁽⁷⁾ The empirical curve assumes a direct energy dependence of the sputtering yield, which is in general agreement with reported helium sputtering data for a number of target materials.⁽⁸⁾ The transition between the two segments forms a peak in the sputter curve at the ionization cut-off energy calculated from the Kinchin-Pease theory.⁽⁹⁾ The threshold energies for sputtering have been determined by the method of Hotston.⁽¹⁰⁾ Since the curves developed in this manner⁽⁷⁾ give yields that are substantially higher than experimentally observed yields, these curves have been adjusted in magnitude to better conform to the available experimental data. Curves for the deuterium and tritium sputtering yields have been reduced by one order of magnitude and those for helium have been reduced by a factor of five. Figure 2 presents the

FIGURE 2. Energy-Dependent Physical Sputtering Yields of Potential First-Wall Materials Irradiated with Mono-Energetic D^+ ions.

resultant monoenergetic sputtering curves for deuterium on several wall materials of interest. Similar curves have been developed for tritium and helium. Experimental data in the low-energy range are shown in Fig. 3.

FIGURE 3. Plot of Selected Energy-Dependent He^{++} Sputtering Data

Figure 4 compares the selected energy-dependent light-ion sputtering curves with available experimental data on niobium. As indicated, the sputtering curves developed here

FIGURE 4. Plot of Light Ion Sputtering Curves for Niobium Showing Comparison with Available Experimental Data

for niobium are in fairly good agreement with similar curves proposed by Behrisch⁽¹¹⁾ for the same target material. In general, the present development gives sputter coefficients that are slightly higher than the corresponding experimental data for low-Z wall materials, and coefficients that are slightly lower than the corresponding experimental

data for the higher-Z wall materials. Sputtering by the neutral D^0 and T^0 particles are assumed to be identical to those for D^+ and T^+ ions, respectively.

In the present study three of the first-wall materials of interest are compounds, viz., BeO , B_4C , and SiC . Since sputtering data for these compounds are very limited, yields equivalent to those for beryllium, boron, and silicon, respectively, have been assumed for these compounds. This assumption appears plausible in view of the data of Kelly and Lam,⁽¹²⁾ which indicate that sputter yields produced by 10-keV Krypton on a number of stable oxides are within a factor of 2-3 of the corresponding metals. The yields for these compounds are assumed to correspond to their stoichiometry, e.g., four boron atoms to one carbon atom for B_4C .

The Sigmund theory is a better representation of the yields observed for heavy (impurity) ion sputtering. Therefore, the self-sputter coefficients used for the calculations are derived from the Sigmund theory with slight modifications at low energies to compensate for electronic losses.⁽⁷⁾ At the lower energies the curves are adjusted to approach a slope of unity on the log S versus log E plot. Figure 5 shows the energy-dependent self-ion sputter coefficients for beryllium, niobium, and tungsten.

FIGURE 5. Energy-Dependent Self-Ion Sputter Coefficients for Beryllium, Niobium, and Tungsten

Large variations in the 14-MeV neutron sputter yields have been reported in the literature for various transition metals. (1-5,13-18) These differences are due primarily to chunk-type deposits that have been observed by some investigators. (13-14) Recent analyses indicate that yields for the chunk-type sputtering, which are dependent on both surface roughness and degree of cold-work, are typically less than 10^{-4} atoms/neutron.⁽¹³⁾ Single-atom sputtering yields in the range 10^{-6} to 5×10^{-4} have been reported. (13-18) A total yield of 10^{-4} atoms/neutron is considered reasonable for the present analysis. Since the contribution of neutron sputtering to the total sputtering yield turns out to be very small for near-term reactors, the results are not very sensitive to variations or uncertainties in the neutron sputtering coefficient.

Chemical interaction between the incident particle and the target material can influence sputtering rates because of the effect of compound formation on lattice displacement energies, on sputtering mechanisms, and on the nature of the sputtered products.⁽¹⁹⁾ Although this so-called chemical sputtering occurs in a number of systems, it is most commonly associated with the formation of hydrocarbons upon bombardment of carbon or graphite by the hydrogen isotopes. (19-27) In line with the chemical interaction energies, the chemical sputtering coefficients, in contrast to the physical sputtering coefficients, are sensitive to the target or wall temperature. For example, greatly enhanced (approximately 10X) chemical sputtering leading to CH_4 formation has been observed for H^+ ion bombardment of graphite at temperatures of 400-700°C. (20-25) Sputtering yields of nearly 0.1 atom/ion are reported by these investigators. For the present investigation, chemical sputtering coefficients for deuterium and tritium incident on carbon were assumed to be a factor

of 10 higher than the physical sputtering yield at temperatures of 300-750°C, and negligible at higher and lower temperatures. Similar enhancement of sputtering yields for silicon-carbide has not been observed, (20, 21, 28) and hydrides of the structural metals are not stable under anticipated wall conditions. Therefore, chemical sputtering has been considered in the present analysis only for the case of carbon or graphite.

The "reflection" coefficient, R , used in the plasma-wall interaction model includes both backscattering and re-emission. The backscattered particles are the incident particles that return from the wall via elastic and inelastic collisions ($\ll 1$ s) whereas the re-emitted particles are those which have penetrated the wall at an earlier time and are subsequently released by diffusion to the surface or by erosion of the wall material. Several models have been developed and experiments conducted to interpret the backscattering and re-emission of light ions (H^+ and He^{++}) from several materials. (29-38) The backscattering coefficients for the light ions typically increase with a decrease in incident ion energy below 1 keV, and the values may exceed 50% at energies below 100 eV. (29, 36-38) The use of such coefficients is appropriate only for the initial startup, since the concentrations of light atoms (helium, deuterium, and tritium) in the surface regions build up in a matter of hours during operation. Therefore, re-emission of the hydrogen isotopes and helium from the surface of the first wall will occur during normal operation. Data of several investigators indicate that high percentages of light ions injected into a variety of target materials are re-emitted after fluences of the order of 10^{17} ion/cm². (30-38) This re-emission is further enhanced by the elevated wall temperatures. For purposes of the present calculation it is assumed that a steady-state is reached and

that the combination of backscattering and re-emission results in the return of almost all of the incident light particles.

For the case of self-ions incident on the first wall, a high sticking probability is expected for a clean metal surface. In addition, the measured sputtering coefficients probably include any backscattered component. Therefore, a near-zero reflection coefficient can be assumed for self ions.

These surface data were incorporated into the calculational model as follows. The mono-energetic sputtering coefficients were averaged over Maxwellian distributions of incident particle energies, with the Maxwellian being characterized by the plasma-edge temperature. These results are given in Table 1. A neutron sputtering coefficient $S_n = 0.0005$ was used for all materials, and a chemical sputtering coefficient $S_{DT} = 0.07$ was used for carbon. Particle reflection coefficients $R_{DT} = R_n = 0.98$ were used in the calculations to represent unity reflection probability and an allowance for a small loss during operation through ports in the vacuum wall, and $R_z = 0.05$ was used to represent the high retention probability for an ion of the surface material.

The charge-exchange re-emission probability was computed from

$$\bar{A}_{cx} = \frac{\overline{\sigma v}_{cx}}{\overline{\sigma v}_{cx} + \overline{\sigma v}_{ion}}, \quad A_{cx} \equiv \bar{A}_{cx} \gamma,$$

where $\overline{\sigma v}_{cx}$ and $\overline{\sigma v}_{ion}$ are averages of the charge exchange ($D^+, T^+ \leftrightarrow D^0, T^0$) and ionization cross sections of Refs. 39-43 over Maxwellian distributions corresponding to the plasma edge ion temperature. The results are $\bar{A}_{cx} = 0.50$ at $T_{DT}^{edge} = 100$ eV, $\bar{A}_{cx} = 0.56$ at $T_{DT}^{edge} = 200$ eV, and $\bar{A}_{cx} = 0.73$ at $T_{DT}^{edge} = 1$ keV. The factor γ represents the probability that a primary charge-exchange event for an incident neutral will result in the re-emergence of a neutral (either directly or as the result of subsequent secondary

TABLE 1. Maxwellian-Averaged Physical Sputtering Coefficients

Material	Plasma Edge Temperature (eV)	Sputtering Coefficient (atoms/part)		
		$S_{DT}^{(a)}$	S_a	$S_z^{(b)}$
Be	60	0.016	0.017	0.26
	200	0.028	0.070	0.35
	1000	0.018	0.115	0.36
BeO	60	0.016	0.017	0.26
	200	0.028	0.070	0.35
	1000	0.018	0.115	0.36
C	60	0.007	0.018	0.26
	200	0.015	0.050	0.35
	1000	0.012	0.079	0.36
B ₄ C	60	0.011	0.017	0.26
	200	0.022	0.060	0.35
	1000	0.016	0.098	0.36
SiC	60	0.0055	0.015	0.26
	200	0.016	0.048	0.47
	1000	0.033	0.160	0.64
Fe	60	0.0015	0.0046	0.27
	200	0.005	0.015	0.59
	1000	0.016	0.067	1.49
Nb	60	0.006	0.0016	0.29
	200	0.002	0.005	0.83
	1000	0.009	0.023	2.62
W	60	0.0001	0.0004	0.11
	200	0.0003	0.0012	0.35
	1000	0.0016	0.0061	1.61

$$(a) S_{DT} = \frac{1}{2} S_D + \frac{1}{2} S_T.$$

(b) Self-sputtering.

charge-exchange events) from the plasma. $\gamma = 0.75$ is used in this work.

The wall-sputtered impurities entering the plasma affect the energy balance both through the transport loss, which goes as Z_{eff} for pseudoclassical and neoclassical scaling and as Z_{eff}^{-1} for trapped-ion-mode scaling, and through the radiative power loss. The radiation model is a modification of a model proposed by Hopkins,⁽⁴⁵⁾ which is based on the results of calculations using coronal equilibrium models.⁽⁴⁶⁻⁴⁹⁾ The results of the

coronal equilibrium calculations have been shown to be good approximations under reactor conditions by comparison with the results of a more general radiative-collisional model.^(50,51)

The model may be summarized as follows: When $T_e \geq T_z$,

$$P_{rad}^z = n_e n_z \left(K_1 Z^2 T_e^{-\frac{1}{2}} + K_2 Z^4 T_e^{-\frac{1}{2}} + K_3 Z^6 T_e^{-3/2} \right),$$

where P_{rad} is the radiated power per cubic meter in W/m³, n_e is the electron density

and n_z is the ion density of the z -th ionic species, T_e is the electron temperature in keV, and T_z is the ionization potential, in keV, for the beryllium-like ion sequence. $K_1 = 4.8 \times 10^{-37}$, $K_2 = 1.82 \times 10^{-38}$, and $K_3 = 4.13 \times 10^{-40}$, when T is in keV and n in m^{-3} . When $T_e \leq T_z$, we insure $P_{rad} \rightarrow 0$ as $T_e \rightarrow 0$ by using,

$$P_{rad}^z = n_e n_z \left(K_1 Z^2 T_e^{-1/2} + K_2 Z^4 T_z^{-1/2} + K_3 Z^6 T_z^{-3/2} \right) \left(T_e / T_z \right)^2.$$

T_z is given by⁽⁸⁾

$$T_z(\text{keV}) = [1.633 \times 10^{-7}(Z-3)^3 + 3.4266 \times 10^{-3}(Z-3)^2 + 5.5574 \times 10^{-3}(Z-3) + 0.529 \times 10^{-3}].$$

The total radiated power is thus given by

$$P_{rad} = \sum_z P_{rad}^z,$$

where the sum includes all ionic species.

The above model was developed from radiation loss studies for nuclei with nuclear charge in the range $5 \leq Z \leq 18$. For impurities with $Z \geq 30$, the model was modified to account for radiation from high- Z materials which are not completely stripped at the 10-keV operating temperatures. In the formula for radiation loss, the nuclear charge, Z , was replaced by the actual ionic charge attained by the impurity at the plasma temperatures. Ionization potentials for various ions up to $Z = 103$ have been tabulated.⁽⁵²⁾ The radiation loss is reduced by a substantial factor for high- Z ions (e.g. 20 for tungsten), relative to a calculation using the atomic number. This reduced radiation power is consistent with results reported in Ref. 51.

ANALYSIS

The analysis was carried out for a specific tokamak reactor model with parameters that are characteristic of the ANL EPR design: $R = 6.25$ m, $A = 2.98$, $I = 6.4$ MA, $q(a) = 2.5$,

$B_t = 4.4$ T. The confinement times were scaled up from the theoretical prediction by a factor $\omega_{TIM} = 1.79$ so that ignition would obtain at $\bar{T} = 10$ keV, in the absence of wall-sputtered impurities and without helium recycling, in the trapped-ion-mode (TIM) transport regime. The thermonuclear power output of a reactor operating under these conditions at $\beta_p = 2.25$ is $P_T = 410$ MWt.

The analysis consisted of a dynamic simulation of the entire burn pulse. Ions escaping from the plasma were assumed to be recycled back as described in Fig. 1, so that essentially total (98%) recycling of deuterium, tritium, and helium occurred unless the particle removal (e.g. divertor) efficiency $\eta > 0$. Deuterium and tritium ion densities were maintained at their maximum allowable value by refueling, subject to the constraint that $\beta_p(t) \leq \beta_p^{\max} = 2.25$. Wall-sputtered impurity ions were assumed to be able to penetrate immediately to the central region of the plasma, where they resided with a confinement time equal to that of the D-T ions. These impurity ions increase the radiative power loss as described in the previous section, modify the particle and energy confinement times ($\tau \propto Z_{\text{eff}}$ for TIM scaling) and reduce the allowable D-T ion density for a fixed $\beta^{\max}$. Supplemental neutral beam heating, up to a maximum power of 80 MW, was used in some cases to offset excessive radiative power losses. The burn pulse simulation was carried out to the point at which the accumulation of helium and wall-sputtered impurities quenched the plasma.

A figure-of-merit for the burn cycle performance is the net electrical power averaged over the burn pulse,

$$P_{\text{net}} = \left[U_T n_T - \frac{U_B}{n_T} - U_{\text{REF}} - U_{\text{PUMP}} - U_{\eta} - U_{\text{PS}}(1 - \eta_{\text{PS}}) \right] / \Delta t_{\text{burn}},$$

where

- U_T = plasma thermal energy to wall during burn pulse
 U_B = beam heating energy during burn pulse
 U_{REF} = refrigeration energy during burn pulse
 U_{PUMP} = coolant and vacuum pumping energy during burn pulse
 U_Ω = plasma ohmic heating energy dissipated during burn pulse
 U_{PS} = energy transferred by plasma driving system during burn pulse

$$= \int_0^{\Delta t} |P| dt$$

η_T = thermal-to-electrical conversion efficiency = 30%

η_B = neutral beam power efficiency = 35%

η_{PS} = energy transfer efficiency = 95%

Δt_{burn} = length of the burn pulse.

The compressive refrigeration power for the superconducting toroidal field coils was

$U_{REF} = 660$ MJ, the coolant and vacuum pumping energy was $U_{PUMP} = 0.02 U_T$, and the energy transferred by the plasma driving system was $U_{PS} \approx 2400$ MJ.

The quantity P_{net} is plotted in Fig. 6 as

FIGURE 6. Effect of First-Wall Surface Material on Power Performance

a function of the length of the burn pulse for several first-wall surface materials. The assumed edge temperature is 200 eV for

all cases. The burn cycle performance that would result in the absence of sputtering is also shown to provide a point of reference. In the absence of sputtering, the minimum burn pulse for which $P_{net} > 0$ is 20 s, including ~4 s for startup. In this case, the burn pulse is ultimately (~157 s) quenched by the accumulation of helium, and the maximum value of P_{net} is 66.5 MW.

Wall-sputtered impurities from a stainless steel (represented by iron) or refractory metal (niobium) first-wall surface have a devastating effect. A substantial supplemental beam heating is required to maintain the plasma at thermonuclear temperatures, resulting in a negative P_{net} , on the order of -200 MWe. The maximum length of the burn pulse could be extended beyond ~20 s by increasing the beam heating power $P_B > 80$ MW, but this would result in an even more negative P_{net} . Initially, the D-T sputtering is the main contributor to plasma contamination, but as the impurity concentration builds up to on the order of 1%, self-ion sputtering becomes a major contributor, as may be inferred from Table 1. The situation is somewhat improved if the plasma edge temperature is less than the 200 eV used in these calculations; however, even for $T_{edge} = 60$ eV, $P_{net} \approx -100$ MWe and the maximum burn pulse is ~20 s. Thus, it appears extremely unlikely that a reactor of this type will be able to operate with a stainless steel or refractory metal wall without some form of impurity control.

One form of impurity control is suggested by Fig. 6, namely to interpose between the plasma and the structural first wall a low-Z material, either as a coating or as a stand-off liner. Burn pulses of ~45-55 s can be achieved with very low-Z surfaces, viz., beryllium, carbon (without chemical sputtering), B_4C , which result in P_{net} about one-half of the value that obtains without wall sputtering. With a small supplemental beam

heating ($P_B = 10$ MW) to offset radiative losses, burn pulses in excess of 60 s with maximum P_{net} of ~35 MWe can be achieved with a beryllium surface. If a carbon surface operates in the temperature range ~400-700°C, then chemical sputtering precludes $P_{net} > 0$, which implies that carbon would be suitable as a standoff liner operating at temperatures in excess of 1000°C but would be unsuitable as a coating operating at 400-600°C. Surfaces with silicon or oxygen compounds are less satisfactory for impurity control in reactors of this type. In the case of beryllium oxide, $P_B \leq 28$ MW was adequate to offset radiative losses, but the accumulation of oxygen in the P_B -limited plasma forced a reduction in the D-T density which eventually quenched the plasma. For the beryllium surface, the self-sputtering rate is about half the D-T sputtering rate, the alpha-sputtering rate is about 5% of the D-T sputtering rate, and the neutron-sputtering rate is negligible.

Another possibility for reducing plasma contamination is to use a low-sputtering first-wall material such as tungsten. Although the plasma performance is better with tungsten than with stainless steel or niobium as the first-wall surface material, the performance with tungsten is considerably inferior to that with a low-Z material such as beryllium. Moreover, the plasma performance is much more sensitive to variations in the sputtering coefficients for a high-Z material than for a low-Z material. In the case of tungsten, the self-sputtering rate is ~30% of the D-T sputtering rate and the neutron sputtering rate is ~10% of the D-T sputtering rate.

The performance summarized in Fig. 6 is based upon a plasma-edge temperature of 200 eV, which corresponds to the maximum in the beryllium sputtering yield curves. Reduced sputtering, hence improved performance, occurs if the plasma-edge temperature is higher or lower for beryllium, as shown in

Fig. 7. At an edge temperature of 60 eV, a burn pulse of 102 s with a maximum $P_{net} = 57$ MWe is obtained with a beryllium surface, which is close to the performance in the absence of wall sputtering. The effect of the plasma-edge temperature is even more dramatic for silicon-carbide, with $P_{net} > 0$ becoming possible for an edge temperature of 60 eV.

Another method of impurity control which has been proposed is to remove ions that escape from the plasma before they strike the wall — e.g., by means of a magnetic divertor. This process can be represented by the efficiency of charged particle removal, η . Results of a series of calculations for a stainless steel first-wall surface and various values of the charged-particle removal efficiency are shown in Fig. 8. For a very low plasma-edge temperature (60 eV) and a very efficient charged particle removal mechanism ($\eta = 0.9$), tolerable equilibrium iron (0.03%) and helium (1.5%) concentrations are maintained and the burn pulse is virtually unlimited. For a more realistic value of $\eta = 0.5$, the performance is marginal and $P_{net} > 0$ requires a low plasma-edge temperature (60 eV) in addition to substantial supplemental beam heating ($P_B = 44$ MW). If the plasma-edge temperature is 200 eV, a very high charged particle removal efficiency ($\eta = 0.9$) and some supplemental beam heating ($P_B = 15$ MW) are required to achieve $P_{net} > 0$. Thus, it appears that the success of a divertor or other impurity control mechanisms based upon charged particle removal depends critically upon the achievement of high particle removal efficiency and upon the operation of the plasma with a low edge temperature. These calculations have not accounted for the significant reduction in energy* of those charged particles which cross the divertor sweep-out region before

*Private communication from A. Mense, ORNL.

FIGURE 7. Effect of Plasma-Edge Temperature on Power Performance

FIGURE 8. Effect of Divertors on Power Performance for Bare Stainless Steel Wall

striking the wall. This might improve the performance of divertors relative to the predictions of Fig. 8.

Combining a low-Z surface with a charged particle removal mechanism reduces the criti-

cal dependence upon high particle removal efficiency. Performance obtainable with beryllium and silicon-carbide surfaces are shown in Fig. 9, for a range of charged particle removal efficiencies. With a

FIGURE 9. Effect of Divertors on Power Performance for Low-Z Coated Walls

beryllium surface, $\eta \geq 0.5$ suffices to achieve very long burns.

The quantitative results discussed above depend upon the particular reactor model and values for the sputtering coefficients used in the calculations, as well as upon the various assumptions in the calculational model, and are subject to change as understanding of the various processes improves. However, the general qualitative features should be relatively independent of the reactor model and the data.

TECHNOLOGICAL FEASIBILITY OF FIRST-WALL SURFACE MODIFICATIONS

On the basis of fabricability, vacuum properties, and economic impact, fusion reactor first walls constructed of transition metal alloys such as stainless steel are favored.⁽⁵³⁾ However, as indicated by the previous calculations, satisfactory plasma performance can only be attained with very low incident particle energies and an efficient divertor and/or supplemental heating. The unacceptable plasma performances were caused primarily by the high radiative losses

produced by the high-Z transition metal impurities. An additional factor that will further degrade plasma performance will be the substantial erosion of the wall by the blistering phenomenon.^(1-5,54-58) For anticipated conditions, erosion rates of structural materials such as niobium or stainless steel by blistering are greater than those by physical sputtering.⁽⁵⁴⁻⁵⁸⁾ These erosion rates are temperature-dependent and peak at the temperature ranges of interest, viz., 400-500°C for stainless steel.⁽⁵⁷⁻⁵⁸⁾

Although complete agreement on the contribution of the blistering phenomenon has not been reached because of uncertainties in incident particle energies and particle energy distribution, the data obtained by monoenergetic bombardments may be a reasonable representation of the 3.5-MeV contribution of the alpha-particle wall current. Effects produced by this component are probably independent of the other low-energy effects. An erosion rate greater than 10^{-1} atom/ion may be expected for stainless steel after a few days operation.^(56,57) This contribution substantially

exceeds that produced by He^{++} sputtering at the low energies (<100 eV) and approaches the sputtering yields of D^+ and T^+ at low energies. Possible synergistic effects such as sputtering and vaporization of blister skins have not been investigated and, although likely to be detrimental, cannot be assessed at this time. Therefore, the conclusions presented in the previous section for the plasma performance with a stainless steel wall are probably quite optimistic.

Several concepts for modifying the first-wall surface are qualitatively assessed in this section: (a) a low-Z material coating on a structural substrate; (2) a separated monolithic low-Z material liner; (3) a carbon cloth liner; and (4) a low-sputter material coating on a structural substrate.

1. Low-Z Coating

The low-Z coating on a structural metal substrate has been proposed as a viable solution to the impurity control problem in EPR.⁽⁵³⁾ This concept utilizes the transition metal (stainless steel) substrate for structural support and the low-Z coating to protect the plasma from the high-Z transition metal atoms. Major considerations in this concept are the flexibility in first-wall design provided by the variety of low-Z coating materials that are considered feasible and the variety of coating procedures available. The coating selection and preparation can be optimized on the basis of its surface characteristics, and the substrate, which provides the structural support, can be selected primarily on the basis of desirable bulk properties.

Fabrication should not be much more difficult than for the simple metal wall discussed above. A substantial technology base exists for applying a variety of coatings to a number of substrate materials.⁽⁵⁹⁾ Much of this technology has been obtained recently under space and fission reactor programs. Although plasma spraying, chemical vapor

deposition, chemical bonding, and sputtering can all be used to coat most of the materials considered,⁽⁵⁹⁾ the plasma spray process appears to be the most appropriate for the present application. Deposition rates necessary to obtain the desired coating thicknesses (~ 100 μm) can be achieved. The porosity and grain size can easily be varied in the plasma spray process to obtain optimum microstructures.⁽⁵⁹⁻⁶¹⁾ Graded coatings, which can also be prepared by the plasma spray process, may be desirable for better coating adherence. However, additional development work and modification of existing coating technology may be required to optimize selected properties for the present application. Since the coating material is not required to serve as a structural member, a wider variety of materials may be feasible. Materials requirements are minimized, since only thin coatings are being considered. As a result, materials cost and availability of more exotic materials are less restrictive for coatings than for low-Z monolithic structures.

The possibility of in situ coating may provide additional benefits for fabrication and repair of first-wall systems. Remote coating preparation by plasma spray, chemical vapor deposition, chemical bonding, and sputtering are all considered feasible, since the required environments can be attained in the vacuum chambers. However, further development work is required to develop an in situ coating technology.

The plasma performance calculations indicated that, on the basis of predicted physical sputtering and reflection coefficients, net power could be achieved in the EPR with several low-Z liner materials. However, other potential sources of wall impurities such as blistering and thermal evaporation were not considered in these calculations. Significant erosion rates from a blistering phenomenon can occur under certain conditions. In some cases the blistering yields

exceed those from physical sputtering. (54-58) However, the blistering phenomenon is strongly affected by the microstructure of the target material. (62,63) Erosion rates produced by helium bombardment are much less for sintered material, both beryllium and aluminum, than for cast or sheet material. Microstructures similar to those of sintered products can be obtained by selected coating procedures, e.g., plasma spray techniques, in which grain size and porosity can be adjusted over significant ranges. It appears that erosion by the blistering phenomenon can be maintained at acceptable levels by appropriate choice of coating parameters.

Depending on the proposed operating temperature and coating material, thermal vaporization may also contribute to impurity effects. Thin coatings on a convectively cooled substrate tend to minimize this contribution by maintaining the low-Z material at lower temperatures than are attained with separated liner concepts. Also, more refractory-type low-Z materials such as B_4C and beryllium oxide can be used if necessary to alleviate this problem.

Two types of impurity effects may be important with regard to the selection of the liner material. One relates to the presence of high-Z impurities in the coating that can reach the plasma by normal erosion phenomena and the second relates to absorbed gases on the wall that may be removed by photodesorption. Since a minimal amount of low-Z material is required for the coating concept, high quality base material can be effectively used to minimize high-Z concentrations. Predominant impurities typically picked up during coating preparation are oxygen and nitrogen. Since these elements are fairly low-Z, moderate amounts are not prohibitive. A major source of plasma impurities in present day physics machines is the desorption of gaseous impurities from the low temperature (room or cryogenic temperature)

first walls. This problem will be considerably different for power reactors in which the first-wall is operated at elevated temperatures. For example, beryllium reacts chemically with oxygen at elevated temperatures to form a very stable compound. At elevated temperatures selected coating materials will chemically react with the impurities, e.g., beryllium with oxygen, to form stable compounds which will reduce the tendency for plasma contamination by gaseous impurity desorption. This effect, which is a major source of impurities in low-wall temperature devices, may not be of significant importance for power reactors.

Vacuum properties of coated walls should not differ substantially from those of a metal wall; in fact, sputter coating of walls in present day physics machines is used to produce clean walls. (64) High helium generation rates are typical of low-Z materials. Since steady-state release rates are reached in rather short times, this produces another impurity source. This effect is not significant for thin coatings, however, as discussed below, it may be significant for thick low-Z liners.

The mechanical integrity of the low-Z coating is an important consideration as it relates to the reliability, lifetime limitation, and failure mechanisms of the coating. An advantage of the coating concept is that the substrate provides the structural support. As a result, micro-cracking of the coating caused by swelling, gas production, or differential thermal expansion may not seriously degrade the effectiveness of the coating as long as it adhered to the substrate. By judicious selection of coating material and coating preparation, optimum properties can be obtained to accommodate these effects. For proposed coating thicknesses of a few hundred micrometers, lifetimes of three to five years are predicted on the basis of sputtering erosion rates in

the EPR. However, evidence exists that a significant fraction of sputtered first-wall material is redeposited on the wall.

The failure mechanism of most concern for the coatings is flaking or loss of adhesion over significant areas. Excessive flaking or spalling of the coating is not tolerable, since exposure of more than a few percent of a high-Z substrate surface, e.g., stainless steel, would probably be unacceptable. This would expose the plasma to excessive high-Z impurity from the substrate. Enhancement of the plasma impurity source would result from vaporization of the loose coating due to loss of heat transfer capability. Any loose particulate material collected at the bottom of the vacuum vessel would likely reevaporize during each cycle because of the lack of heat removal capability. This problem may be alleviated if the flakes are vaporized and subsequently vapor-deposited on the wall at the end of a burn cycle. In either case, a capability for recoating appears essential, and an in situ coating capability may have important consequences.

2. Low-Z Separated Monolithic Liner

With respect to effects on plasma performance, a low-Z separated liner has much in common with the low-Z coating discussed above. The major differences relate to the technological aspects of fabricability and mechanical integrity. Therefore only the significant advantages and disadvantages of the separated liner in comparison with the coating will be discussed.

Although fabrication, installation, and repair of separated liners appears to be more difficult than that for coatings, several possibilities have been proposed that appear technologically feasible.⁽⁶⁵⁻⁶⁷⁾ A major difference from the coating relates to the much larger quantity of material required, which has a significant impact on cost and materials availability if the more exotic low-Z materials are used. Since a separated

liner must provide a degree of its own structural support, the materials selection is probably more limited, and since most concepts operate with radiatively cooled separated liners, problems inherent to high temperature operation will be encountered.

In most cases the impurity control capability of a separated liner should be similar to that for a coating of the same material, since the physical sputtering and reflection coefficients should be the same in both cases. If chemical sputtering is important, as in the case of carbon or graphite, the wall temperature becomes critical. A separated liner will probably operate at temperatures above the chemical sputtering range for carbon, while the operating temperature of a coating is probably near the peak of the chemical sputtering range. It is assumed that monolithic separated structures of the sintered product type can be used to maintain "blistering" erosion rates at acceptable levels. However, this requirement may further limit the selection of materials.

Impurity contributions from thermal vaporization will be more critical for the stand-off liner than for the coating because of the inherently higher operating temperature of the radiatively cooled liner. Decreases in thermal conductivity of the liner material as a result of thermally induced or radiation-induced micro-cracking will lead to higher surface temperatures that may subsequently cause excessive thermal vaporization. Lower thermal conductivities characteristic of materials with substantial porosity, which is required to facilitate gas release and to minimize blistering, will also affect the operating temperature limitations.

Additional impurity effects produced by binders, which are commonly used in many sintered ceramic liner materials, must be considered. Helium generation in thick

low-Z liners may also produce significant effects if complete helium release occurs at high temperatures, as expected. For example, the helium generation rate in an ISSEC⁽⁶⁸⁾ could exceed the helium generation rate from the fusion reaction. However, this is not expected to be excessive for liners less than 1 cm thick.

The fusion reactor vacuum requirements will be greater for a separated, monolithic liner of either the bumper or shingle type, since the total surface area in the vacuum vessel will be substantially increased, i.e., probably a factor of three or four. The pumping problem may be further complicated by the geometric consideration, viz., the thin annulus behind the liner which is connected to the toroidal chamber.

Several problems relating to the reliability and mechanical integrity appear to be more severe for the separated liner than for the coating concept. Since the liner must provide its own structural support, micro-cracking and dimensional instabilities caused by thermal and neutronic effects may lead to premature failure. Accelerated deterioration of the liner caused by higher temperatures and more severe thermal cycling may also occur as a result of reduced thermal conductivity of the liner material during operation. Erosion of the liner by sputtering, blistering, etc., should not seriously affect the useful lifetime of the liner.

The failure mechanisms associated with the monolithic separated liners appear to be more critical than those of the coating concept with respect to the effect on reactor operation and subsequent repair and maintenance. Fracture of a liner section not only could expose the plasma to substantial areas of high-Z vacuum wall, but the fractured remnants could be a source of excessive plasma contamination caused by overheating and vaporization. Repair and maintenance of the

separated liner plates would probably be more difficult than in situ recoating.

3. Carbon Curtain Liner

Since the carbon curtain liner has much in common with the separated monolithic liners, only those factors that are unique to the curtain will be discussed. The fabrication considerations with respect to technological feasibility, materials cost, and materials availability are all favorable for this concept. However, methods of attachment of the curtain have not been analyzed in detail. Since carbon is particularly susceptible to chemical sputtering, high-temperature operation, with its attendant problems, is mandatory. Gross differences in the behavior of carbon cloth after bombardment by helium and hydrogen have been observed.^(20-25,69)

Thermal vaporization of graphite may be critical for this concept because of thermal conductivity effects related to the geometric considerations. Low thermal conductivity through the cloth related to strand-to-strand heat transfer coefficients for the large number of fibers (of the order of a thousand per thread bundle) may create excessive temperatures at the plasma surface, leading to vaporization.

Vacuum properties of the graphite cloth will require additional pumping capability relative to a metal or low-Z coated wall. Initial outgassing will be much more difficult than for some of the other concepts, because of the additional surface area and structure of the cloth.

Mechanical integrity limitations and unattractive failure modes may limit the usefulness of this concept. Although substantial variation in the degradation of graphite cloth from neutron and ion bombardment has been reported in the literature, severe degradation of the cloth has been reported for several conditions.^(21,25,69) It is well known that neutron radiation effects in graphite are strongly dependent on the type

of structure. The structure of the graphite filaments is similar to structures in which radiation-induced swelling and damage is large. Light ion irradiation can also lead to severe degradation of the cloth fibers. A major concern with the graphite cloth concept is the mode of failure. Degradation and fraying or breaking of the filaments as a result of neutron and ion bombardment may cause accelerated deterioration of the cloth and enhanced contamination of the plasma. Frayed or broken filaments protruding toward the plasma region will have a reduced heat transfer capability and will probably overheat and vaporize, further increasing plasma contamination. This potential for enhanced degradation of the cloth liner resulting from accelerated damage of frayed or fragmented pieces hanging in the plasma region is a major concern relating to the viability of this concept.

4. Low-Sputter Coating

As indicated by the light ion sputtering curves in Fig. 2, some materials, particularly tungsten, have much lower sputtering coefficients at low incident particle energies than do the other materials. Tungsten also has a relatively high threshold energy, e.g., 217 eV for D^+ ,⁽¹⁰⁾ for light ion sputtering. As a result, the feasibility of a low-sputtering first-wall surface has been assessed. Although the light-ion sputtering coefficients are very low at ion energies below 1 keV, the allowable plasma impurity levels of these high-Z ions are extremely low. Therefore, impurity contributions from other sources such as blistering and neutron sputtering, which were negligible for the low-Z surfaces, become more important for this concept.

Tungsten is considered to be the prime candidate for the low-sputtering surface. Because of fabrication difficulties with tungsten, viz., welding and machining, the most appropriate near-term approach for this

concept is a thin tungsten coating on a stainless steel substrate. This approach minimizes the quantity of material required and alleviates many of the fabrication and joining difficulties. Several coating procedures such as plasma spray, chemical vapor deposition (CVD), and sputtering have been used for applying tungsten coatings.⁽⁵⁹⁾ As in the case of the low-Z coatings, the plasma spray or detonation gun processes^(59,60) are preferred in order to obtain appropriate microstructures to minimize blistering.^(62,63) Most of the other technical considerations and the failure mechanisms will be similar to those discussed above for the low-Z coatings. Since tungsten has favorable high-temperature properties, thermal vaporization should be minimal. The maximum temperature limitations will probably be established by the substrate. A low-sputtering tungsten coating appears as technologically feasible as a low-Z coating; however, the low-Z coating seems preferable from a plasma contamination point of view. A major consideration is the substantial increase in sputtering yield with an increase in incident ion energy. The plasma performance becomes extremely unfavorable for the tungsten liner if incident ion energies exceed a few hundred eV.

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