"NATURAL" LOW Z COATINGS FOR FUSION REACTORS

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Coating the walls of a vacuum chamber with Be or some other low Z material has been proposed as a possible solution to the problem of high Z impurities in plasmas. The properties of any coating will be highly dependent on (1) the nature of plasma impurity deposition on walls, and (2) radiation-induced solute segregation. The latter process can spontaneously produce low Z coatings in some alloys and drastically alter metallic interdiffusion in a reactor environment. We have studied the required parameters of coatings (thickness, composition, purity, etc.) and possible means of in situ deposition. We present results of a preliminary survey of coatings, substrates, and deposition methods which are most compatible with reactor operation. We also outline experiments presently underway which will measure the stability of coatings in a radiation environment.

1. INTRODUCTION

The performance of reactor-like plasmas has been studied in detail for the Argonne Experimental Power Reactor, a device sized to produce net power at minimum cost, based on a detailed plasma-wall interaction model containing sputtering and plasma impurity losses [1,2]. This study concluded that low Z coatings [1,3] on the walls of the vacuum chamber would probably eliminate the need for a diverter if pulse lengths of ≤100 sec were acceptable. The study also concluded that low Z coatings are probably needed even for reactors with divertors. The low Z coating would provide a number of advantages other than reducing plasma contamination; one example being increased freedom to pick separate materials to provide bulk and surface properties.

The behavior of the plasma wall system with low Z coatings would be determined by the mechanisms shown in Fig. 1. Impurity atoms flow into the plasma primarily due to sputtering or arcing [4]. During and after each cycle, the plasma impurities are deposited on the walls by a process analogous to condensation. Assuming the vacuum chamber is valved closed at the end of a plasma discharge, it seems reasonable to expect that most of the metallic impurities should be adsorbed on the wall and primarily gaseous products should be removed by the vacuum pumps. In spite of diffusion, the stability of a thin coating seems likely in a radiation environment. Radiation-induced solute segregation, a process by which solute atoms in a metal are dragged to surfaces or boundaries by radiation-induced defect currents, should be sufficient to compensate for diffusive mixing and insure that Be coatings on stainless steel, for example, will not diffuse away [5].

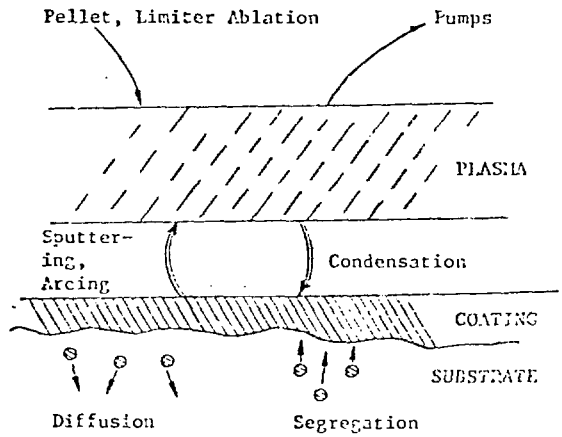

Fig. 1. Processes affecting wall coatings.

In existing devices, the comparatively low powers (<5 MW) transmitted to the walls are generally absorbed by limiters which occupy a small fraction of the wall area. As the power levels transmitted to the wall become larger (100-300 MW in a reactor), it will probably be necessary to spread the plasma power over the first wall as evenly as possible. This mode of operation should tend to make the impurity deposition, and the coating produced, more uniform than present machines.

2. CHOICE OF COATING MATERIAL

The Argonne Experimental Power Reactor (EPR) study calculated net power produced from tokamak reactors with a number of different wall materials, concluding that carbon, boron, B_4C, BeO, and beryllium had roughly comparable effects in the plasma, assuming only physical

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sputtering was considered [1,3]. Chemical sputtering from carbon could considerably increase the overall sputtering yield and make carbon unacceptable. Both B_4C and BeO, in addition to beryllium, seemed to be acceptable as wall coating materials, based on plasma contamination. Other materials as heavy as Ti have also been suggested. However, as shown in Fig. 2 [6], this could produce a large increase in impurity losses.

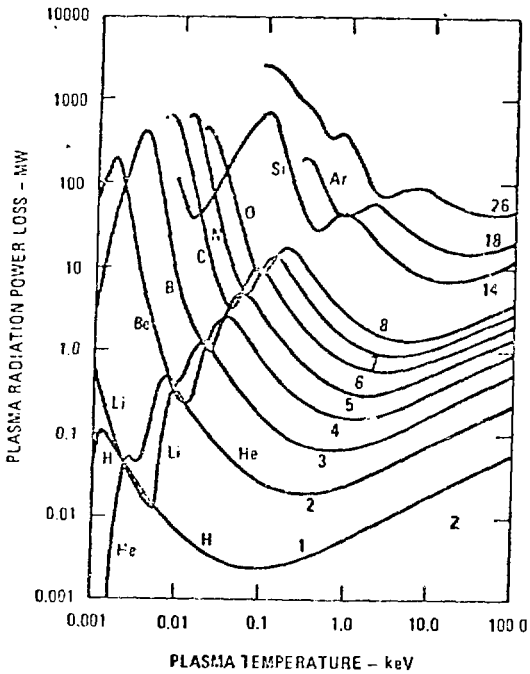

Fig. 2. Power radiated by a 0.1% impurity. $V = 400\ m^3$, $n_e = 1.6\ 10^{20}/m^3$ [6].

3. THICKNESS OF COATINGS

The minimum coating thickness can be determined by three constraints: (1) the thickness must be sufficient to suppress substrate sputtering, (2) the average thickness must be sufficient to cover the entire surface, assuming that the coating material will not be deposited uniformly (a random distribution being more likely), and (3) the coating should probably also be thicker than the range of plasma particle implantation on the wall material to avoid radiation enhanced diffusion. Range-energy curves for hydrogen ions in various materials [7], and experimental data in PLT [8], show that plasma particles incident on the walls with energies of about 100-200 eV should penetrate roughly 100 Å (or less) into the wall material.

The first two constraints require coatings only a few monolayers thick to suppress substrate sputtering. Long-term stability in a reactor environment seems to require coatings of somewhat greater thickness to avoid radiation-enhanced diffusion, perhaps a minimum coating thickness of 200-2000 Å.

4. RADIATION INDUCED SOLUTE SEGREGATION

Any coating on a metallic substrate would be affected by thermal diffusion. This process would cause atoms to diffuse a distance $x = \sqrt{Dt}$ where the distance x is expressed in terms of a diffusion constant D and a time t. The diffusion constant is generally expressed in the form $D = D_o \exp(-Q/RT)$ where D_o is the frequency factor, Q is the activation energy for diffusion and R and T are the gas constant and absolute temperature in °K. Diffusion parameters have been measured by Ananin, et al. [9] for nickel into Be and Ni-Be alloys, which give the scale this effect for Ni in Be, $D_o = 0.2\ cm^2/sec$ and $Q_o = 58$ kcal/mole. Assuming a thickness of 100 Å and a temperature of 500°C (773°K) the Be coating would be expected to last about 10^5 sec. This lifetime would be barely acceptable. Diffusion is not always the dominant process involved, however. Radiation-induced solute segregation has been shown to dominate over a wide range of temperature and radiation flux.

Radiation induced solute segregation is a process which uses the coupling between defects and solute atoms, combined with the motion of radiation-induced defects to defect sinks (surfaces or boundaries) to produce a net flow of solute atoms [5]. Considerable experimental data exists for stainless steel, where the effect was discovered, but Be - Ni is a simpler system and has been studied in more detail. In Be - Ni, it has been shown that even at high temperature (625°C), radiation-induced segregation can occur strongly enough to move most of the beryllium within 1000 Å of the surface, to the surface. (Fig. 3)

The relative magnitudes of the radiation induced segregation and diffusion are determined primarily by the irradiation temperature and rate of production of defects; hence, the radiation level. Solute segregation should be the dominant process under the conditions of a fusion reactor first wall. (T 450-500°C, radiation dose 1×10^{-6} dpa/s) [5]. (Fig. 4)

For some applications, it may be acceptable to create the coating by simply using a wall material with Be alloyed into it, as the radiation would cause the Be to migrate to the surface. In most cases, however, it will probably be necessary to produce a coating in situ by condensing a thin layer of coating material onto the surface from the plasma.

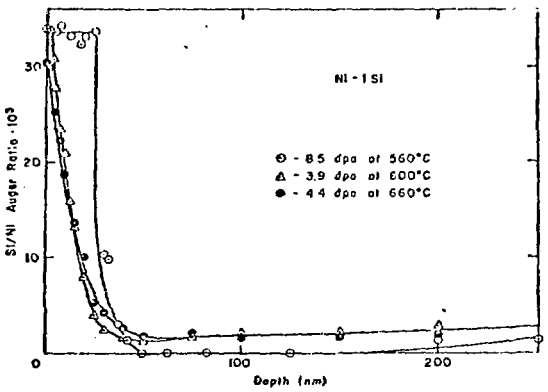

Fig. 3. Measured concentration vs depth profiles for an Ni-1 at. % Si alloy irradiated to 8.5 dpa at 560°C, 3.9 dpa at 600°C, and 4.4 dpa at 660°C. Measurements of Be in Ni, though more difficult, have shown the same effects with somewhat poorer resolution [10].

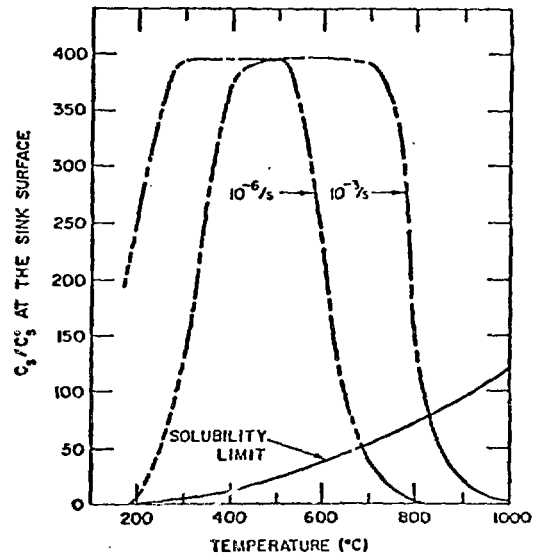

Fig. 4. Steady-state surface-concentration ratio of solute C_s/C_s^o as a function of irradiation temperature for displacement rates of 10^{-6} and 10^{-3} dpa/s. The solubuility limit for Be and Ni is indicated. $C_s^o = 10^{-3}$, $H^m_{isa} = 1.28$ eV, $H^b_{isa} = 1.88$ eV, $H^b_{vs} = 0$ and 2000 Å foil [5].

5. SURFACE PROPERTIES

While the surface produced when the impurities in a plasma condense on the walls will not be well controlled, this mechanism should be the dominant one and the surface produced should be the naturally occurring surface in a fusion reactor. The wide variety of possible methods of discharge termination (impurity-dominated, "normal" current ramp down, runaways, disruptions, etc.) will probably produce a large variety of surface conditions in the reactor, and this method of coating and maintaining the first wall may be the best way of achieving repeatability from discharge to discharge. It should be noted that discharge cleaning and titanium gettering are required to provide this function in existing machines.

The overall stability of a thin high Z coating over long periods of time seems to be inadvertently demonstrated at low temperatures by the results in PLT [11]. In that device, the material was deposited from a thick limiter, perhaps by means of unipolar arcs. If the coating was thin everywhere, however, the PLT results seem to imply a slow "distillation" of coating material away from limiters and toward the parts of the vacuum chamber that are cooler and more remote from the plasma. Impurities (O_2, N_2, CO, etc.) will also be introduced onto the wall from real and virtual leaks and in the absence of regular discharge cleaning, these could eventually dominate the composition of the first wall. For these reasons, it seems desirable to consider a mechanism for maintaining the surface thickness and diluting the concentrations of unwanted impurities. We have considered in some detail the introduction of pellets composed of coating material into the plasma to create and maintain the coating.

6. METHODS OF APPLICATION

Many mechanisms, sputtering, chemical vapor deposition, electrolytic deposition, thermal evaporation, etc., are capable of producing deposits of thin films on substrates. We have looked primarily at the one mechanism of wall coating that seems most appropriate to tokamak reactor operation; i.e., building up the coating layer from impurities in the plasma. The PLT results with tungsten have shown that reasonably homogenous layers can be obtained which are stable over a large number of shots [11]. Studies of EPR operation assuming only physical sputtering have also shown that a significant fraction (0.05) of a monolayer of wall material cycles between the wall and the plasma if the pulses are long; thus, the first wall is effectively redeposited every 20 shots or so [1]. This high redeposition rate makes the mechanism by which the coating was originally deposited much less important.

While large machines such as JET or the ANL/EPR might deposit significant fractions of a monolayer per shot, smaller machines with more

surface/plasma volume and shorter pulses require a somewhat different approach. We have been looking at means by which the impurity levels in these smaller devices can be raised to provide sufficient fluxes of impurity atoms to the wall to build up a coating. Such methods include injection of pellets, use of thickly-coated or solid limiters, laser ablation of solid samples, or use of wires inserted in the plasma. Gaseous molecules H_nZ_m containing impurity atoms (Z) could also be injected into the plasmas.

An example of impurity injection has been calculated using the parameters of the proposed APEX tokamak (R = 50 cm, R = 15 cm) [12]. These calculations show that the plasma can absorb a large amount of Be before being extinguished. It seems reasonable to expect density ratios of $n_{Be}/n_H \sim 1$ for small machines, yielding about 0.03 monolayers/shot.

7. EXPERIMENTS

Radiation-induced solute segregation has been studied primarily by means of ion bombardment. Experiments are presently underway (ANL-Sandia) to determine if neutrons alone produce the same effects; specifically (1) are coatings stabilized by neutron irradiation? and (2) can coatings be created by neutron-induced solute segregation?

Experimentation in plasma devices is necessary to determine the suitability of different low Z materials. Questions such as bonding ability, appropriate cleaning procedures, behavior in the presence of other impurities, effects of implanted hydrogen, thermal behavior, sputtering properties, etc., should be systematically studied for substrates coated by plasma deposition.

8. CONCLUSIONS

We have reviewed arguments demonstrating that low Z coatings should provide advantages in the operation of all magnetically confined plasma devices. The thin coatings should be stable due to radiation-induced solute segregation, a process which will force small atoms (Be, Si) to the surface and bury larger ones (Mo, Al, Ti). This effect should tend to make a Be coating on stainless steel both self-cleaning and self-healing.

Condensation of plasma impurities on vacuum walls should be the dominant mechanism controlling the microstructure of the wall surface in both large and small devices, in the absence of leaks. Ablation of solid pellets can be used to artificially introduce impurities into a plasma in a small machine. The surface produced when these impurities condense on the walls should closely approximate the surface environment in a reactor.

9. ACKNOWLEDGEMENTS

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