Paper presented at the 2nd Topical Meeting on "Fusion Reactor Materials" in Nuclear Materials.

Conf-810831--100

CONF-810831--100

DE83 007871

MATERIALS SELECTION FOR THE U.S. INTOR DIVERTOR COLLECTOR PLATE

R. F. Mattas, B. Misra, D. L. Smith
Argonne National Laboratory
Argonne, Illinois 60439

G. D. Morgan & M. Delaney
McDonnell Douglas Astronautics Co.
St. Louis, Missouri

R. Gold
Westinghouse
Pittsburgh, Pennsylvania

*Work supported by the U.S. Department of Energy.

MATERIALS SELECTION FOR THE U.S. INTOR DIVERTOR COLLECTOR PLATE

R. F. Mattas, B. Misra and D. L. Smith
Argonne National Laboratory

G. D. Morgan and M. Delaney
McDonnell Douglas Astronautics Company

R. E. Gold
Westinghouse Fusion Power System

The divertor collector plate in the INTOR reactor will be subjected to high heat, particle, and neutron fluxes, making it the most severely damaged torus component. The collector plate is composed of a protection plate, which is directly exposed to the particle flux, and a heat sink which provides support for the protection plate and carries the water coolant. The high-Z refractory metals have been considered for use as the protection plate material, and austenitic stainless steels and copper alloys have been considered as the heat sink material. Tungsten and Type 316 stainless steels have been selected for the protection plate and heat sink, respectively. The protection plate has a sputtering lifetime of 1.75 y at a 50% duty factor, while the heat sink is expected to last the lifetime of the reactor.

1. INTRODUCTION

The impurity control system in INTOR is a single null poloidal divertor located at the bottom of the plasma chamber, as shown in Figure 1.(1) The purpose of the divertor is to divert and collect the ionized particles that have escaped from the plasma as well as the sputtered particles from the first wall. A summary of the operating conditions is shown in Table 1. The total energy to the divertor is 80 MW, which is equally divided between the inner and outer channels. A total of 70 MW of that energy impinges directly on the divertor collector plates resulting in high surface heat and particle fluxes, in addition to the usual neutron flux. The inner plate is placed at an angle of 30° and the outer plate is placed at an angle of 14.5° with respect to the separatrix. The angular placement reduces the peak surface heat flux to 2 MW/m^2 and the peak particle flux to $1.5 \times 10^{22}/m^2$-s.

Table 1. Divertor Operating Conditions

Design concept	Single null poloidal divertor
Total energy to divertor	80 MW
Ion energy to divertor plates	35 MW
Electron energy to divertor plates	35 MW
Charge-exchange energy to throat and walls	5 MW
Radiation energy to throat and walls	5 MW
Energy to channels - outboard	40 MW
- inboard	40 MW
Peak energy flux to channels at null (normal to separatrix) - outboard	8 MW/m^2
- inboard	4 MW/m^2
Total ion flux to divertor	$5.5 \times 10^{23}/s$
Average energy of ions	400 eV
Peak ion flux to channels at null (normal to separatrix) - outboard	$6 \times 10^{22}/m^2s$
- inboard	$3 \times 10^{22}/m^2s$

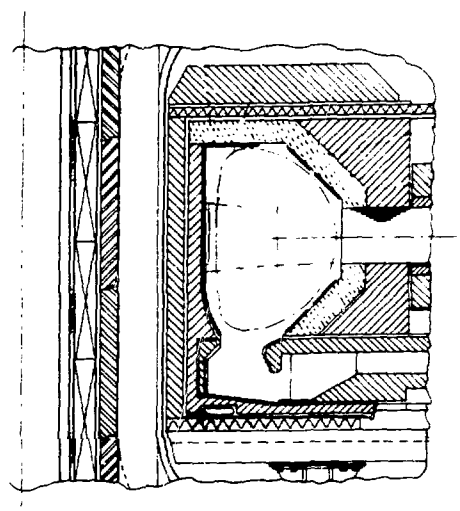

Figure 1 : Cross section of INTOR reactor showing divertor at bottom of plasma chamber.

The severe operating conditions mean that the divertor collector plate is the most severely damaged torus component, and hence the materials considerations are crucial to the overall design. The collector plates will potentially be subjected to large temperature and stress gradients, large physical sputtering rates, and radiation damage in the form of swelling, embrittlement, and creep of the plate materials. The concept chosen for the collector plate design is to separate the problems of sputtering from those of cooling and structural support.

The plate design, shown in Figure 2, consists of a low sputtering protection plate that is mechanically attached to a heat sink composed of a standard structural alloy. The protection plate is eroded during particle bombardment and eventually requires replacement. The mechanical attachments result in poor thermal conductance between the plate and heat sink, but they allow the plate to freely expand and rotate as the temperature changes during the burn cycle, thus minimizing the thermal stress. During the burn cycle, the plate temperatures increase to 2000-2400°C, at which point 40 to 50% on the incident heat is radiated back to the divertor chamber and plasma chamber, reducing the thermal gradient in the protection plate and the heat flux incident upon the heat sink.

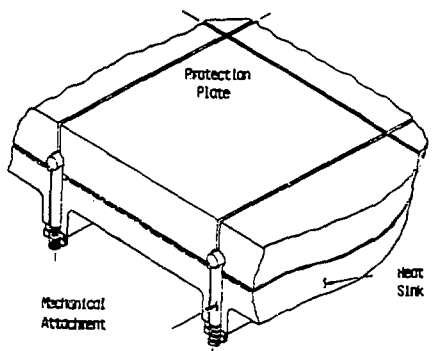

Figure 2 : Divertor collector plate design.

2. PROTECTION PLATE MATERIALS

The principal requirements for the protection plate material are a low sputtering coefficient and adequate strength at the high operating temperatures. In addition the material should have a high thermal conductivity, a low coefficient of thermal expansion, and a low elastic modulus in order to minimize the thermal stresses. The materials that most closely meet these requirements are the high-Z refractory metals such as W, Mo, Ta, and their alloys.

The physical sputtering coefficients for W, Ta, and Mo are shown in Table 2. The coefficients are calculated from a model by Smith. (2,3) The predicted values indicate that W has the lowest sputtering at 400 eV. A comparison of the thermophysical properties at 2000°C is shown in Table 3. (4,5) The materials have comparable thermophysical properties, but W is slightly favored since it has the highest melting point. The mechanical properties at 2000°C are compared in Table 4. (5,6) At this temperature, all the materials are above the recrystallization temperature, and therefore, they are all quite weak. In particular, the creep-rupture strength is very low. The low strength means that the protection plate must operate at low stresses in order to obtain an acceptable lifetime. Tungsten clearly has the highest strength at these temperatures, and primarily for this reason, it is capable of withstanding the highest thermal stress. Because of the advantages of the lowest sputtering and highest elevated temperature strength, W has been selected as the reference material for the protection plate.

Table 2. Sputtering Coefficients of Potential Divertor Collector Plate Materials At 400 eV

Atomic Species	Material		
	Mo	Ta	W
O	7.40×10^{-2}	2.42×10^{-2}	2.22×10^{-2}
C	5.55×10^{-2}	1.81×10^{-2}	1.66×10^{-2}
He	1.48×10^{-2}	4.37×10^{-3}	3.89×10^{-3}
D	5.84×10^{-3}	1.24×10^{-3}	1.01×10^{-3}
T	9.31×10^{-3}	2.07×10^{-3}	2.34×10^{-3}
Self	4.58×10^{-1}	2.99×10^{-1}	2.79×10^{-1}

Table 3. Thermophysical Properties of Divertor Plate Materials at 2000°C

Property	Material		
	Mo	Ta	W
Melting Point (K)	2883	3269	3683
Thermal Conductivity (W/m-K)	71	87	102
Thermal Expansion (x 10 /K)	7.0	7.6	5.4
Specific Heat (J/kg-K)	390	170	168
Elastic Modulus (GPa)	165	130	290

The advantages and disadvantages of using tungsten are related to the high operating temperatures. Radiation damage will readily anneal out of the material at elevated temperatures ($\sim.65\ T_m$) so that no radiation swelling, creep, or embrittlement are expected. However, recrystallized tungsten is brittle at temperatures <300°C (5), and therefore special precautions are required during initial start-up and shutdown to prevent cracking. Fatigue at elevated temperatures is a major concern, but there are no fatigue data available

to evaluate the problem. Two additional concerns, high temperature chemical sputtering and surface emissivity will be discussed in detail.

Table 4. Estimated Mechanical Properties of Divertor Plate Materials at 2273 K

	Mo	Ta	W
0.2% YS (MPa)	22	15	35
UTS (MPa)	25	25	65
Ductility Range, %	40-60	35-45	20-40
1,000 h Creep Rupture Strength (MPa)	2	<1	9.0
Thermal Stress Parameter[a]	135	132	227

[a] $\frac{(\text{Thermal conductivity}) \times (0.2\% \text{ Yield Strength})}{(\text{Elastic Modulus}) \times (\text{Thermal expansion coefficient})}$; high values desirable.

Besides deuterium, tritium, and helium, impurities will be directed at the divertor plate. In particular, the particle flux is expected to contain an oxygen ion concentration of 0.5%, which can cause oxidation/chemical sputtering. Tungsten interacts with oxygen at temperatures above 500°C, and the primary high temperature oxide, WO_3, volatilizes above ~1000°C. The predicted volatilization loss rates for the maximum particle flux operating conditions are illustrated in Figure 3. The curves in the figure are based upon a model by Batty and Stickney.(7) The model assumes that at lower temperatures (<1800 K), the rate controlling step of the overall process is the adsorption of O_2 on the tungsten surface where it reacts to form an equilibrium mixture of volatile oxide species. The adsorption fraction is called the "equilibrium probability", ξ_o, and the results of calculations indicate that ξ_o increases rapidly with increasing temperature. At high temperatures, where $\xi_o \to 1$, the volatilization rate is controlled by the equilibrium thermodynamics. At the expected operating temperatures of 1700-2500°C, the predicted volatilization rate is 10^{-2} to 10^{-3} of the incoming oxygen particle flux (solid curve). Since the incoming particles will be ionized rather than diatomic molecules, ξ_o is likely to be much greater than the values calculated from laboratory experiments. In the worst case where $\xi_o = 1$, every incoming oxygen atom will be able to participate in the formation of tungsten oxide. This case is also plotted in Figure 3 (broken line). At temperatures below 1900°K, the tungsten loss rate is equal to one-third of the oxigen particle flux, since the dominant oxide species is assumed to be WO_3. The maximum loss rate is calculated to be 2.5×10^{19} atoms/s-m^2 which is ~ 3/4 of the loss rate predicted for physical sputtering. The volatilization rate is predicted to reach a minimum of 2×10^{17} atoms/s-m^2 at 2400°K. There are large uncertainties associated with the chemical sputtering predictions, however.

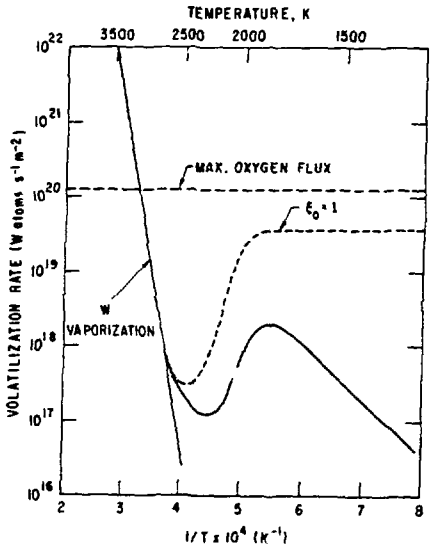

Figure 3 : Predicted W volatilization rate due to oxygen particle flux.

The actual environment at the collector plate is considerably more complex than the model described above. After volatilization, a tungsten oxide molecule can interact with the incoming particles in several ways. The molecule may proceed to strike and stick to the nearest cold surface, it could undergo ionization, or it could undergo dissociation. An ionized molecule would be re-directed back to the plate by the sheath potential. The neutral atoms of a dissociated molecule would also be ionized and redeposited on the plate. At this time, little is known about the redeposition and redistribution of sputtered material. Further work, both experimental and theoretical, is required to understand chemical sputtering of tungsten.

The surface emissivity will have a significant effect on the tungsten operating temperatures because the plate is largely radiation cooled. The emissivity of solid materials depends on the roughness and oxide characteristics as well as the wavelength of the emitted radiation and the material temperature.(8) In general, the emissivity increases as the temperature increases and the wavelength decreases. The

emissivity of tungsten has been measured over a large temperature range and for a range of surface conditions.(9) The total hemispherical emittance for polished tungsten at 2000-2400°C varies from 0.28 to 0.34.(9) At these temperatures, no oxide is present which means that the only means for increasing the emissivity is to increase the surface roughness. At 2200°C, a roughened surface increases the emissivity to 0.4-0.65, and therefore, it is concluded that appropriate fabrication techniques (e.g., grooving or sandblasting) can increase the emissivity to 0.5 to 0.6. Since the top surface is exposed to energetic particles, a major concern is the effect of sputtering on surface roughness. Unfortunately, no experimental data taken under the appropriate conditions are available to evaluate the actual emissivity of a sputtered tungsten surface.

3. HEAT SINK MATERIALS

The purpose of the heat sink material is to provide structural support for the tungsten plates and to contain the pressurized coolant. The material must maintain its mechanical integrity and dimensional stability under the severe radiation, thermal, chemical, and stress conditions of the divertor environment. Two classes of metals have been examined as heat sink materials - copper alloys and austenitic stainless steels. The primary advantage of copper and copper alloys is their ability to withstand much higher surface heat fluxes. This advantage is due to the extremely high thermal conductivity of copper. On the other hand, stainless steels are generally stronger and capable of higher operating temperatures (~500°C vs ~300°C). The effects of high neutron fluences are also better understood in stainless steels because of the larger data base.

Neutron irradiation of copper is limited to a damage level $\lesssim 1$ dpa.(10) The peak swelling temperature of pure copper is ~325°C (0.44 T_m) and the swelling rate is high (0.2-0.5%/dpa). Radiation hardening and embrittlement is also observed.(11) A particular concern is the embrittlement of cold worked copper. For example, 20% cold worked copper that was irradiated to <1 dpa at ambient temperature had a total tensile elongation of <1%.(11) In contrast, the radiation properties of Type 316 stainless steel are far superior to those of copper. (Since radiation effects in austenitic stainless steels have been reviewed extensively elsewhere, they will not be discussed here.) It is estimated that the radiation effects in Type 316 stainless steel are not life limiting for the INTOR operating conditions.(1) Therefore, there is an incentive to use stainless steel as a structural material, if the heat fluxes and the associated thermal stresses can be reduced to an acceptable level.

4. LIFETIME ANALYSIS

The protection plate lifetime is likely to be dependent upon the sputtering rate of tungsten. The effective physical sputtering coefficient for tungsten has been estimated during the INTOR design study to be 2.2×10^{-3}.(1) For an incident particle flux of $1.5 \times 10^{22}/m^2$-s, the material loss rate is 5.2×10^{-10}m/s. The resulting lifetime for a protection plate that can lose 15 mm of thickness before replacement is 1.75 y for a 50% duty factor. As noted earlier, there is considerable uncertainty in the value for the sputtering coefficient due to possible chemical sputtering and the effects of redeposition. Thermal fatigue due to the cyclic operating cycle may also influence the lifetime, but there is insufficient information available for an evaluation. Thus, although the protection plate appears to be capable of multi-year lifetimes, considerable experimental effort is needed to acquire important physical property information.

The major lifetime concern of the stainless steel heat sink is the potential for high cyclic stresses leading to fatigue failure. In order to qualify austenitic stainless steel, it must be shown that the heat sink can be designed to meet the ASME stress and fatigue criteria. The ASME design curve for fatigue incorporates safety factors of two in stress or twenty in cycles to failure, whichever is lower, over the mean fatigue failure curve.(1) The fatigue strain in the heat sink depends upon the maximum and minimum heat loads transmitted by the protection plate. One of the advantages of the radiation cooled collector plate design is that the heat load to the heat sink is reduced. The peak load during the burn is 1.1 MW/m^2 and the minimum heat load during the dwell period is 0.6 MW/m^2. For these conditions, the fatigue lifetime of the heat sink is expected to exceed the reactor lifetime. Details of the analysis are given elsewhere.(1) Since in addition, austenitic stainless steel has adequate radiation damage resistance, the heat sink is expected to last the reactor lifetime.

REFERENCES

[1] W. M. Stacey, et al., "U.S. INTOR Conceptual Design," USA INTOR/81-1 (1981).

[2] D. L. Smith, J. Nucl. Mater., 75 (1978) 20.

[3] D. L. Smith, Proc. Workshop on Sputtering Caused byPlasma Surface Interactions, Conf-79-07-75 (1979).

[4] Y. S. Touloukian, ed., Thermophysical Properties of High Temperature Solid Materials (The MacMillan Company, New York, 1967).

[5] T. E. Teitz and J. W. Wilson, Behavior and Properties of the Refractory Metals (Stanford University Press, CA, 1965).

[6] J. B. Conway and P. N. Flagella, Creep-Rupture Data for the Refractory Metals to High Temperature (Gorden and Breach Science Publishers, New York, 1971).

[7] J. C. Batty and R. E. Stickney, Oxidation of Metals, 3 (1971) 331.

[8] D. P. DeWitt and J. C. Richmond, Theory and Measurement of the Thermal Radiation Properties of Metals, in E. Passaglia ed., Techniques of Metals Research, Volume VI, Part 1, (Interscience Publishers, New York, 1972).

[9] Y. S. Touloukian and D. P. DeWitt, eds., Thermophysical Properties of Matter, Volume 7 (IFI/Plenum, New York, 1970).

[10] R. W. Knoll, A Literature Review of Radiation Damage Data for Copper, University of Wisconsin, UWFDM-384 (1980).

[11] Japan Contribution to the International Tokamak Reactor Phase-I Workshop (1981).