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EVALUATION OF LIQUID METAL PROTECTION OF A
LIMITER/DIVERTOR IN FUSION REACTORS*

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ABSTRACT

The liquid metal protection concept is proposed mainly to prolong the lifetime of a divertor or a limiter in a fusion reactor. This attractive idea for protection requires studying a wide range of problems associated with the use of liquid-metals in fusion reactors. In this work the protection by liquid-metals has concentrated on predictions of the loss rate of the film to the plasma, the operating surface temperatures required for the film, and the potential tritium inventory requirement. The effect of plasma disruptions on the liquid metal film is also evaluated. Other problems such as liquid metal compatibility with structural materials, magnetic field effects, and the effect of liquid metal contamination on plasma performance are discussed. Three candidate liquid-metals are evaluated, i.e., lithium, gallium, and tin. A wide range of reactor operating conditions valid for both near term machines (INTOR and ITER) and for the next generation commercial reactors (TPSS) are considered.

This study has indicated that the evaporation rate for candidate liquid metals can be kept below the sputtering rate for reasonable operating temperatures and plasma edge conditions. At higher temperatures, evaporation dominates the losses. Impurity transport calculations indicate that impurities from the plate should not reach the main plasma. One or two millimeters of liquid films can protect the structure from severe plasma disruptions. Depending on the design of the liquid metal protection system, the tritium inventory in the liquid film is predicted to be on the order of a few grams.

INTRODUCTION

The limiters and divertors in fusion reactors will be operating under harsh environment. Not only must a divertor/limiter structure

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cope up with a large heat loads it must also withstand severe surface erosion during both normal and off-normal operating conditions. Under most conditions the major mechanism of erosion during normal operation is predicted to be physical sputtering from plasma particle bombardment. Erosion due to surface vaporization can occur during off-normal operating conditions following a high energy deposition as a result of unipolar arching, run-away electrons, and plasma disruptions. In addition, these eroded materials must have a minimum impact on the plasma performance since significant impurities may lead to unacceptable radiation losses.

The liquid metal protection concept is proposed mainly to provide continuous replacement of eroded surface material on divertors/limiters plates. Without such replacement, the limiter or the divertor may have to be replaced several times during the course of reactor operations. For minimizing thermal stresses and surface temperature the thickness of these reactor components should be minimized. However, the losses from sputtering and vaporization make it difficult to operate the reactor with bare thin metallic materials. Liquid metal protection for the metallic structures has been proposed in several studies.¹⁻² This protection may take various forms such as thin film protection,³ droplet protection,⁴ and a pool liquid metal protection.⁵ A thick film layer can also be used as a coolant for the structure.¹ The concept analyzed in this study involves a thin liquid metal film slowly flowing over a divertor target, with a separate coolant to cool the divertor structure. The presence of this continuously flowing protective layer over the structure can significantly prolong the lifetime of such components. The thin protective layer with a separate coolant may be more attractive than a thicker layer that also acts as a coolant. This is mainly due to the larger volume and the higher flow velocity required when using the liquid film as a coolant. For such a design, the magneto-hydrodynamic losses (MHD) will be higher, tritium inventory will be larger, and it may

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have a relatively negative effect on the breeding blanket. In addition, bubbles may be formed in the liquid as a result of plasma particle bombardment. These bubbles may reduce the efficiency of the heat transfer system and may increase erosion rates due to bubble explosions.⁶

The analysis presented in this study of the use of thin liquid metal films to protect the divertor plate have concentrated on estimating the loss rate of the film to the plasma, the surface temperatures required for the film, the effect of plasma disruption on the film and the potential tritium inventory requirement. Three candidate liquid metals were considered, i.e., lithium, gallium, and tin. Alloys of these liquid metals may also be used for protection to improve the performance and to reduce or prevent the interaction with the structural material beneath.

LIQUID FILM MATERIAL SELECTION

The materials for the liquid metal film must fulfill certain requirements for a safe and successful operation in the reactor. One requirement for the film material is to have a low melting point. This is desired such that a wide range of operating temperatures can be achieved, not restricting the reactor operation by a narrow temperature window. Another important requirement for the liquid film is to have a low vapor pressure. This is desired not only to reduce film losses but mainly to minimize the plasma contamination from the evaporating atoms. A similar requirement to minimize the plasma contamination is for the film to have a low sputtering erosion. Compatibility with the structural materials is an important selection criterion and may narrow the choice for the film material.⁷ Such compatibility requires no chemical reaction between the film and the structure beneath that may result in corrosion of the structure or the formation of compounds that are not favorable and may affect the performance. Proper film wetting conditions and maintaining a uniform thin film flow are also important factors in the compatibility with the structure materials. One study indicated that with liquid tin as the protective layer, only molybdenum and tungsten are known to give proper wetting and offer adequate resistance to chemical attack.³ Liquid gallium may be a reactive metal at relatively low temperatures while tin is not a reactive metal especially with water. However, the use of gallium or tin alloys can result in better performance and less interaction with the structural material.⁶ Liquid Li is highly reactive with water and is not recommended for use in such an environment. The stability of the liquid film during normal and off-normal reactor operations due to various existing forces is another important factor. Slowly moving thin

liquid film is expected to be stable under the existing electromagnetic forces in the reactor. During disruptions, the stability and erosion of the liquid metal film will depend on the magnitude of the forces as well as on the disruption parameters.⁸

THERMAL HYDRAULIC ANALYSIS

The system analyzed in this study consists of a thin liquid metal layer of 1 mm thickness flowing over the divertor collector plate. The three potential candidate liquid metals, i.e., lithium, gallium, and tin are investigated with two candidate structural materials, i.e., stainless steel and molybdenum. Both water and liquid lithium are current candidates for the main coolant of the divertor structure. Liquid lithium film is not considered to use with a water coolant because of safety considerations. Therefore, water coolant is used for divertors/limiters that are using either tin or gallium thin film for protection, and liquid lithium coolant is assumed to cool the structure when a lithium thin film is used to protect the divertor collector plate. The physical properties as a function of temperature for the liquid metals used in this study are taken from Ref. 15.

The film heat transfer coefficient, h , for water coolant inside the coolant tubes is given by⁹

$$h = 0.023 \left(\frac{V^{0.8}}{D^{0.2}} \right) f(T) \quad (1)$$

where V is the water velocity (m/s), D is the internal diameter of the coolant tube (m), and

$$f(T) = \left(\frac{\rho}{\mu} \right)^{0.8} P_r^{0.33} K \quad (2)$$

where ρ is the density, μ is the viscosity, K is the conductivity and P_r is Prandtl number. For a water velocity of 10 m/s, water average temperature of about 50°C, and a tube diameter of 10 mm, the coolant film transfer coefficient on the water side is about 5×10^4 W/m² · °K. The temperature rise across the coolant film, ΔT_c , is then given by

$$\Delta T_c = \frac{Q}{h} \quad (3)$$

where Q is the total surface heat flux. The average temperature rise across the structural material, ΔT_s , is given by

$$\Delta T_s = \frac{Q x_s}{K_s} \quad (4)$$

where x_s is the thickness and K_s is the thermal conductivity of the structural material.

If liquid lithium is used as the thin film protective layer on the divertor plate, liquid lithium as the main coolant is assumed to be used for the divertor. The film heat transfer coefficient, h , across the lithium coolant can be estimated from Nusselt number, Nu , as

$$h = \frac{Nu K}{D} \quad (5)$$

Using $Nu = 8$, a value recommended for liquid lithium in a magnetic field environment, the film heat transfer coefficient is about $4 \times 10^4 \text{ W/m}^2 \cdot \text{K}$.

The surface temperature of the protective liquid metal film can then be given as

$$T_f = T_c + Q \left(\frac{1}{h} + \frac{x_s}{K_s} + \frac{x_f}{K_f} \right) \quad (6)$$

where x_f and K_f are the thickness and the conductivity of the liquid film respectively.

Figure 1 shows the liquid film surface temperature for 1 mm film thickness over 2 mm molybdenum structure as a function of the surface heat flux. With water coolant a Ga and Sn film result in much lower surface temperatures than lithium film with lithium coolant. This is mainly because of lithium inlet coolant temperature has to be greater than the melting point. An average lithium coolant temperature of 250°C is assumed, while a 50°C average temperature is assumed for water. Water coolant is simpler to use than lithium coolant especially in a high magnetic field environment. In addition lower surface temperatures are very important to keep evaporation losses low. However, the minimum required film temperature adjacent to the structural material, i.e., the film back temperature, must exceed the melting point of the liquid film. In the case where liquid tin is used with the molybdenum structure the minimum surface heat flux required to ensure that the entire tin film is in the liquid phase is more than 5 MW/m^2 . To accommodate lower surface heat fluxes, the coolant parameters along with the structural material thickness can be adjusted to ensure that the minimum temperature of the protective layer is above the melting point. For example, using a 6 mm molybdenum structure thickness and a water coolant temperature of about 100°C will ensure that all the tin protective film will be in the liquid phase for a surface heat flux of 2 MW/m^2 . Figure 2 shows a comparison of the film surface temperature for both molybdenum and stainless steel structure. Because of the lower conductivity of stainless steel, its film surface temperature is quite higher than that of the molybdenum structure. As a result tin film can be used with relatively thinner

stainless steel structure than molybdenum at lower surface heat fluxes. In the case of a lithium film layer, reducing the structural material thickness or the film thickness itself will reduce the surface film temperature. However, if any portion of the divertor plate is exposed to low or no heat fluxes at all, the coolant temperature may have to be increased significantly to ensure that all the surface temperatures of the film are above its melting point. For water cooled divertor plate the required water coolant temperature may reach 300°C . This can complicate the design and in this case lithium coolant or liquid metal alloys may be more attractive. For example, the eutectic alloy of gallium, indium, and tin (62.5 Ga, 21.5 In, 16 Sn) is a liquid at temperatures only greater than 10.7°C and has many desirable features.¹⁶

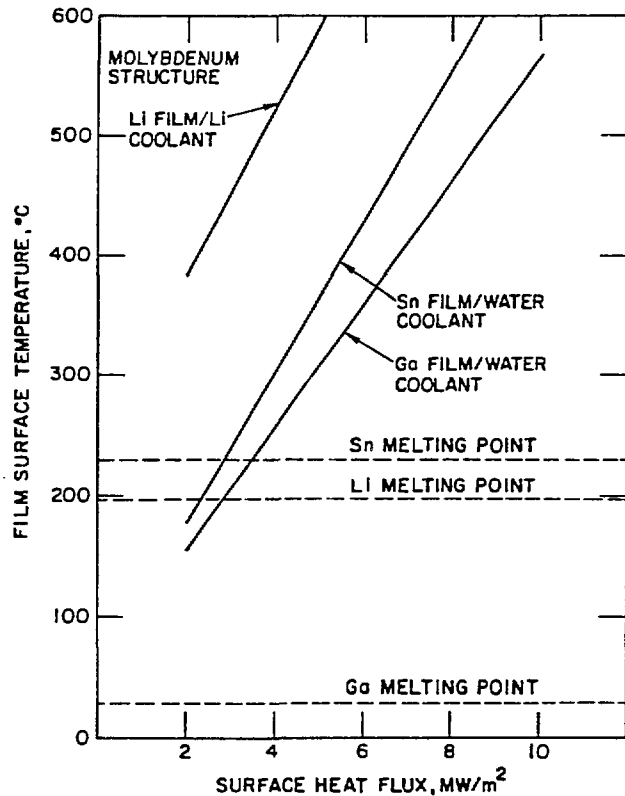


Figure 1

Film surface temperature as a function of the surface heat flux.

EVAPORATION AND SPUTTERING EROSIONS

One major concern about using liquid metals for protection in fusion reactors is their high vapor pressures compared to solid materials. Such high vapor pressures may introduce additional impurities to the plasma. In this section the rate of surface evaporations as a function of temperature are calculated and compared to the sputtering erosion of the three liquid metals considered.

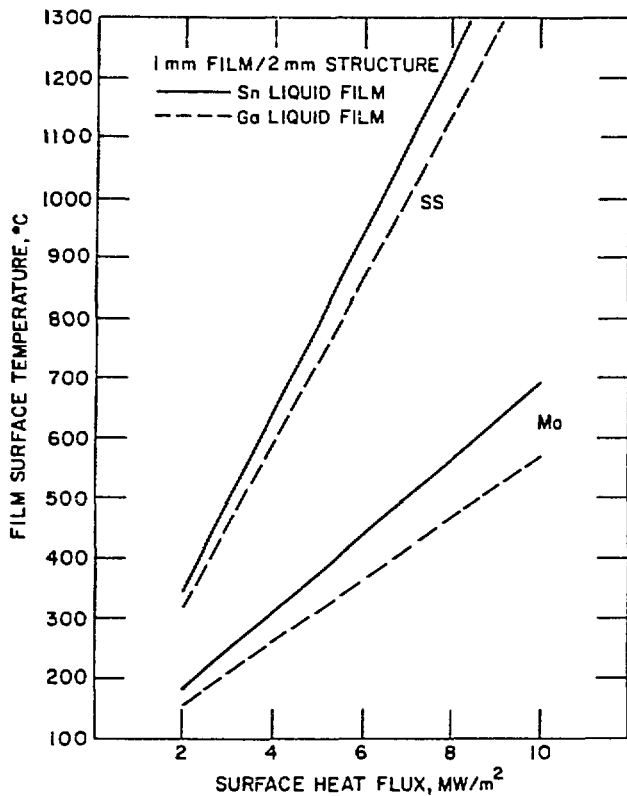


Figure 2
Comparison of film surface temperature for both molybdenum and stainless steel structure.

The rate of surface erosion of the liquid metal film due to evaporation as a function of the surface temperature can be given by¹⁰

$$\dot{x}(T) = 5.81 \times 10^{-2} \alpha \frac{P_v(T)}{\rho} \frac{M}{T} \text{ cm/sec} \quad (7)$$

where α is the sticking probability of the metal atoms on the surface ($\alpha \approx 1$), $P_v(T)$ is the equilibrium vapor pressure in torr at temperature $T(^{\circ}\text{K})$, ρ is the density of the metal (g/cm^3), and M is the atomic weight. Vapor pressure data for the liquid metals used in this study are taken from Ref. 15.

Physical sputtering by plasma particles bombardment on reactor components is predicted to be the major mechanism of erosion during normal operation. A significant data base for physical sputtering of candidate materials has been developed for solid targets in recent years. The sputtering yields for liquid metals have been calculated in this study assuming binding energies for the liquids similar to those of solids. This accuracy is considered to be within the range of other uncertainties in the plasma surface interaction

analysis and assumed adequate for this study. A simple model to calculate the sputtering yield in atoms per ion is given by¹¹

$$S(E) = \frac{500}{U_0} Z_1^A (Z_2 - 1.8)^2 \left(\frac{M_1 - 1}{M_2}\right)^{1.5} E_f \quad (8)$$

where

$$E_f = \frac{E - E_{th}}{(E - E_{th} + 50 Z_1^B Z_2)^2}$$

$$E_{th} = \frac{(3 M_1 + M_2)^2}{4 M_1 M_2} U_0$$

$$B = 40 / (Z_1 + 40)$$

$$A = B - 0.2$$

where Z_1 , Z_2 and M_1 , M_2 are the atomic numbers and mass numbers of the incident particles and target atoms, respectively; U_0 is the binding energy in eV, and E is the incident particle energy in eV. In calculating the sputtering coefficients, the energy of the impinging D-T ions is assumed to be 100 eV and a typical flux of $10^{24} \text{ m}^{-2} \text{ s}^{-1}$ to the divertor is used.

Figure 3 shows the sputtering and evaporation losses at different film surface temperatures for the three liquid metals considered. It can be seen that lithium has the highest evaporation rate and the highest sputtering erosion. The sputtering yield for lithium is near maximum around 100 eV while that for both tin and gallium will increase significantly at higher energies. At higher temperatures evaporation dominates the losses. Lithium evaporation losses are lower than sputtering losses for lithium surface temperatures up to 500°C while for tin and gallium the evaporation losses do not exceed the sputtering losses for temperatures up to 1000°C. Liquid tin and gallium thus allow for a larger temperature gradient design window and their evaporation losses are very small.

The effect of sputtered and evaporated atoms on plasma performance is a very important factor. Impurity transport calculations for a high recycling divertor have indicated that most of the sputtered atoms from solid tungsten return to the divertor surface and redeposited.¹² However, this issue is a major concern not only for liquid metals but also for solid materials as well and should be further analyzed with experimental verifications. Although the uniformity and properties of the redeposited material are still a major concern

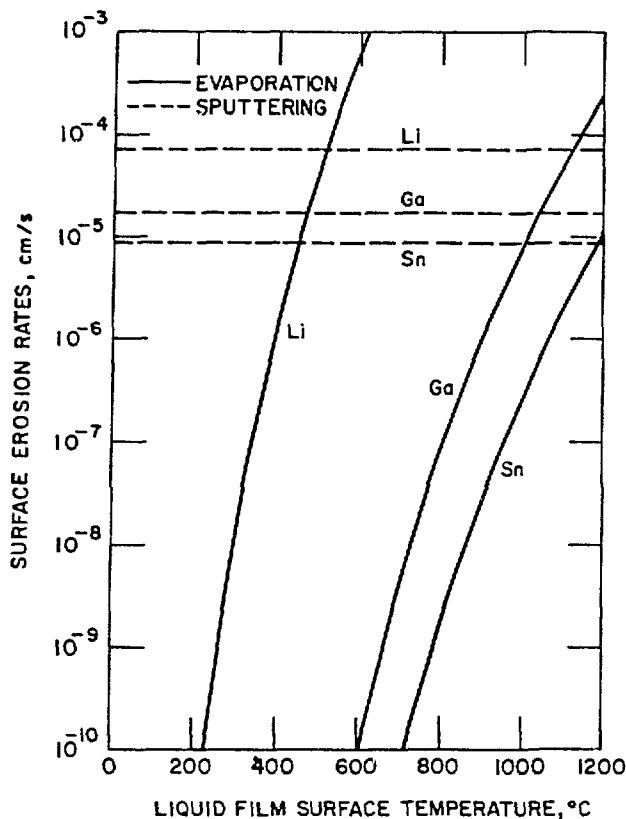


Figure 3
Surface erosion rates for the liquid film as a function of temperature.

for solid materials, liquid metals have a great advantage in this matter.

DISRUPTION ANALYSIS

Plasma disruptions are still one of the main life-limiting criteria for fusion reactor components. The surfaces facing the plasma are subject to repeated melting and/or vaporization during the disruption. Depending on the severity of the disruption event, the repeated loss of material through vaporization and possibly through melting can lead to a complete erosion of parts of the reactor components such as the divertor and hence failure of the design. With the liquid metal protective layer flowing over these components the effect of the disruption on the structural components may be eliminated. In this section the response of the liquid metal film to plasma disruption is studied. Because the liquid metal being continuously replenishable, the losses during the disruption are not important. However these losses determine the minimum film thicknesses required for full protection against the disruption. The model used in this analysis is a slightly modified version of a previous model.¹³ Only a brief

summary is given below. The time-dependent heat conduction equation is solved in two zones. One zone being the liquid film and the other being the solid structure. In both zones the material properties are allowed to vary with the temperature. The initial temperature distribution prior to the disruption event is determined from the steady state heat flux and the coolant temperature as discussed earlier. The surface boundary condition during the disruption requires partition of the incident energy into conduction, evaporation, and radiation. It is assumed that during the disruption the liquid film is stationary and does not flow. This is a good assumption since the disruption time is very short and the film flows very slowly.

The primary disruption parameters that determine the severity of a disruption event are mainly the energy deposited per unit area (i.e., the energy density), the duration of this energy deposition or the disruption time, and the frequency of disruptions or the total number of disruptions expected during the lifetime of the reactor. The frequency of disruption is not important in the case of liquid metal protection since the film can be easily supplied. Disruption times can be as short as a fraction of a millisecond, and disruption energy densities can be as high as 2000 J/cm² on divertor plates. Figure 4 shows the film thickness vaporized for the three liquid metals as a function of disruption time for one energy density of 500 J/cm². Lithium has the highest vaporization losses and gallium has the lowest. For disruption times greater than 50 ms, no losses are expected from gallium and tin films although for similar conditions, a considerable melting from a bare stainless steel surface is predicted.¹⁴ The minimum film thickness required can then be estimated from the disruption parameters such as the energy deposited and the disruption time. The disruption time during thermal quench of the plasma has been recently estimated to be around 0.1 ms. Figure 5 shows the minimum film thickness required as a function of the energy density deposited in 0.1 ms disruption time. For 2000 J/cm² deposited, more than 2 mm lithium film thickness is required to protect the structure while only 0.8 mm gallium or 1.2 mm tin film thicknesses are needed for protection. As discussed earlier a 2 mm Li film used with lithium coolant may result in very high surface film temperatures during normal operation. This will lead to excessive evaporation losses from the film. However these calculations are done without the effect of vapor shielding,¹³ i.e., the self-protection of the liquid layer as a result of its own vaporized material. The vaporized liquid metal atoms are expected to interact with the incoming plasma ions and thus shield the liquid film from further vaporization. This will result in a reduction of

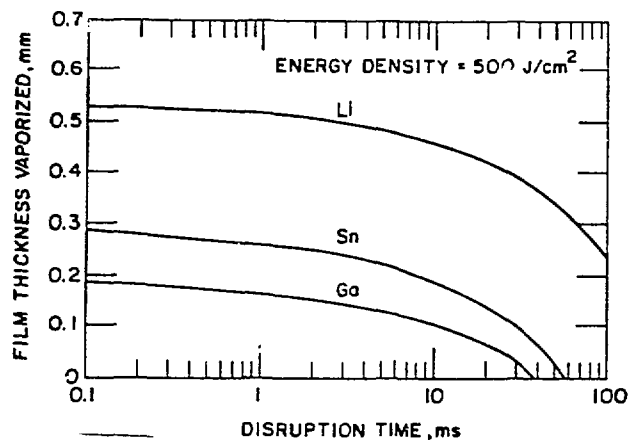


Figure 4

Liquid film thickness vaporized as a function of disruption time.

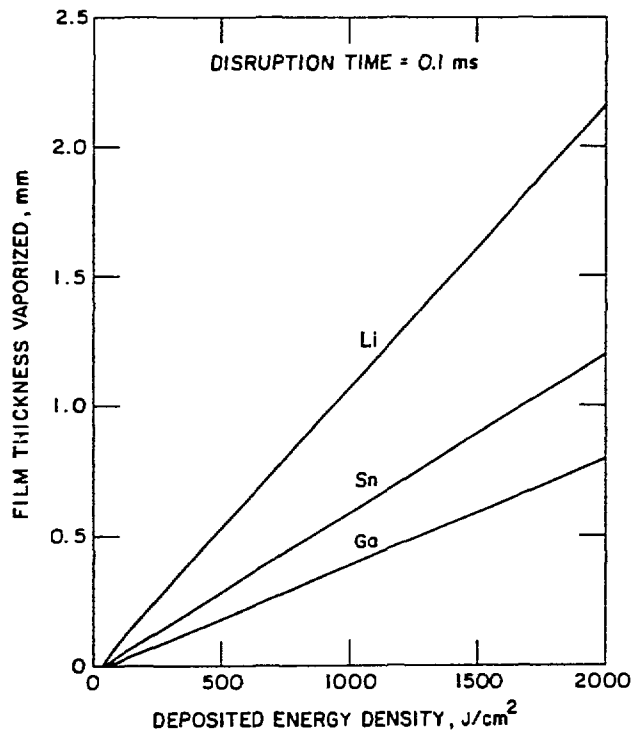


Figure 5

Liquid film thickness vaporized as a function of the deposited energy density.

the required minimum thickness of the layer by at least a factor of 2 for the conditions presented in this study. As a result, the vapor shielding may then ease the requirement for thicker films.

The tritium inventory in a thin liquid lithium protective layer is calculated to be on the order of a few grams. It appears then that the inventory is not a problem. The permeation through the structural material into the main coolant can be even further reduced by using a permeation barrier and without seriously affecting the inventory. The tritium inventory is even less of a problem with liquid tin being the protective layer, since tin has a very low hydrogen solubility. Gallium is also expected to have low inventory. However, lack of data, possibility of compound formation such as hydrides and a formation of an oxide layer on the surfaces of these liquid films may raise a concern. A more detailed analysis is required in this area.

SUMMARY

The studies presented in this paper have indicated that the evaporation rate can be kept below the sputtering rate for a reasonable operating temperature. Lithium has much higher evaporation losses than both tin and gallium, and has a slightly higher sputtering coefficient. The evaporation losses are less than the sputtering losses up to 500°C for lithium and up to 1200°C for tin. At higher temperatures, evaporation dominates the losses. Impurity transport calculations indicate that impurities from the plate should not reach the main plasma. Liquid tin and gallium allow for a large temperature range design window and can be used with water coolant systems. One or two millimeters of liquid tin, Ga, or Li can provide a full protection against severe plasma disruption conditions. A tin layer with water coolant provides much lower surface temperatures than a lithium layer with a lithium coolant. The tritium inventory in the liquid lithium layer is on the order of a few grams. It appears not to be a problem. It is even less of a problem with liquid tin.

CONCLUSION

Thin liquid metal films are investigated as a method of protection for divertors/ limiters in fusion reactors. The analyses have shown that one or two millimeters of liquid film can provide adequate protection for the solid structure from the harsh environment existing in the reactor during normal and off-normal operating conditions. However, there are several issues that need to be studied carefully before any certain conclusions are made. Among these issues are the sputtering erosion rates for liquid metals and the extent of plasma contamination from surface erosion. This is an important issue for solid divertors as well. Although it appears that liquid tin with water coolant offers a wider range of

acceptable and desired operating conditions than lithium film with lithium coolant, high Z-materials may not be acceptable for adequate plasma performance. This is even more important for low edge plasma temperatures. Other issues requiring further investigation are the film compatibility with the structural material, the effect of high magnetic fields on the film, tritium behavior, and sufficient data base for candidate liquid metals. Nevertheless the idea of liquid metal protection offers some attractive features and the feasibility of the concept should be pursued further.

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