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Erosion Damage of Nearby Plasma-Facing Components during a Disruption on the Divertor Plate*

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DISCLAIMER

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Intense energy flow from the disrupting plasma during a thermal quench will cause a sudden vapor cloud to form above the exposed divertor area. The vapor-cloud layer has been proved to significantly reduce the subsequent energy flux of plasma particles to the original disruption location. However, most of the incoming plasma energy is quickly converted to intense photon radiation emitted by heating of the vapor cloud. This radiation energy can cause serious erosion damage of nearby components not directly exposed to the disrupting plasma. The extent of this "secondary damage" will depend on the divertor design, disrupting plasma parameters, and design of nearby components. The secondary erosion damage of these components due to intense radiation can exceed that of the original disruption location.

1. INTRODUCTION

Disruption damage to plasma-facing components (PFCs) remains a major obstacle to a successful tokamak concept. The high energy deposited in short periods on plasma-facing materials (PFMs) can cause severe erosion, plasma contamination, and structural failure of these components. The initial energy flow released at the start of a disruption will cause a sudden vapor cloud to form above the surface of the exposed area. This shielding layer has been proved to significantly reduce the energy flux to the original disruption spot, thus leading to a substantial reduction in erosion rate [1]. Most of the incoming plasma kinetic energy is, however, converted to radiation energy by the expanding vapor-cloud front. Such a large amount of radiation energy can cause significant damage to nearby components not directly exposed to the initial disruption, particularly in a closed divertor configuration such as in the current ITER design [2]. For an open divertor configuration, this problem will be less severe because the radiation will spread over a much larger area.

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The models developed in the comprehensive magnetohydrodynamic code A*THERMAL-S have been extended to study the secondary damage of nearby components due to vapor radiation. Originally, three major modeling stages of plasma/material interaction were developed with sufficient detail to accurately simulate disruption effects [3]. Initially, the incident plasma particles from the disrupting plasma will deposit part of their energy on the PFC surface. Models for particle deposition and material thermal evolution that take into account phase change, moving boundaries, and temperature-dependent thermophysical properties, together with kinetic models for surface vaporization, were developed to predict the thermal behavior of PFCs. A shielding vapor cloud will quickly form in front of the incoming plasma particles. Shortly thereafter, the plasma particles will be completely stopped in this vapor cloud. Continuous heating of the vapor cloud will ionize, excite, and generate photon radiation. The kinetic energy of the incoming plasma particles is therefore transformed into radiation energy.

Detailed models for the magnetohydrodynamics and heating of the vapor cloud that shields the original surface and the newly developed secondary vapor cloud were then developed. Finally, models for radiation transport and deposition throughout the vapor cloud were developed to estimate the net heat flux transmitted to the PFMs and to other nearby components. Figure 1 is a schematic illustration of the various interaction zones and processes during the plasma/radiation/material interactions of a thermal quench disruption. The intense radiation from the primary vapor cloud will strike adjacent components in direct line of sight and can cause a secondary vapor cloud of the component's material to form above its surface. The strong primary vapor radiation has already been demonstrated, in laboratory disruption simulation experiments, to cause erosion damage of near-target components [4].

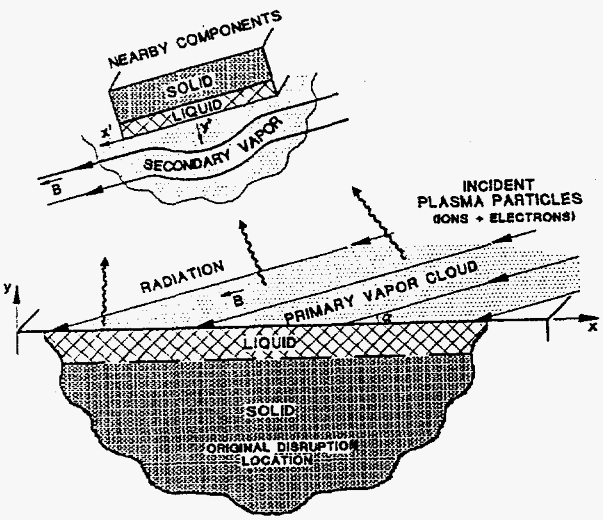

Figure 1. Schematic illustration of interaction phenomena during a disruption.

Because of the importance of radiation transport in the vapor-cloud regions, a self-consistent approach [5] to calculate the actual radiation field has also been developed and implemented in the A*THERMAL-S code. The optical properties of both the "original," primary, and secondary vapor-cloud plasmas are calculated at each time-step during the course of the disruption. The relevant atomic data bases of candidate materials are implemented in the code. The kinetic rate equations are then solved for each ion level population at every time-step. The radiation transport equation is then solved separately for both line- and continuum-generated spectra. The self-consistent model also takes into account the multispecies effect, i.e., mixing between the incoming plasma particles and the primary vaporized material.

To evaluate the extent of the indirect disruption damage to nearby components caused by the primary vapor radiation of the original divertor material, the A*THERMAL-S code was significantly enhanced and new models were developed. Detailed physics of both plasma particles and photon radiation interaction with solid/liquid and vapor materials in a strong magnetic field with various configurations are enhanced and implemented in the self-consistent model. The transport and deposition of the propagating radiation, generated from the primary vapor cloud, in nearby PFCs and in the resulting secondary vapor cloud and its own radiation transport in these components are also calculated in detail. Depending on divertor configuration and design, the energy deposited from the divertor vapor radiation is high enough to cause severe melting and erosion of nearby components. Melt-layer erosion of metallic nearby components can also be significant [6]. The net erosion of these components can, in fact, exceed that of the original disruption location. This can be due to secondary vapor optical properties, vapor diffusion losses, melt layer splashing, and geometrical effects.

2. EVALUATION OF SECONDARY DAMAGE

The amount of energy deposited on nearby components from the primary vapor radiation depends on many parameters, such as distance from the divertor plate, size and orientation of components, and magnetic field structure adjacent to these components. Such parameters are used as input to the A*THERMAL-S code [7].

Figure 2 shows the time dependence of the power density transmitted to the original target and the radiated power density from the developed vapor cloud to other components. Typical plasma disruption parameters are assumed where the incident plasma energy is 10 MJ/m^2 deposited within 100 μs. The kinetic energy of the incident plasma ions is 10 keV. An oblique toroidal magnetic field of 5 T at an angle of 2° is assumed near the original disruption location of the divertor plate [8]. Initially, the power reaching the divertor target is equal to that of the incident disrupting plasma power due to direct deposition of the plasma particles. Shortly after that, the power to the primary target sharply decreases due to shielding and attenuation by the ablated material. After the plasma ions have completely stopped in the target vapor, the primary target heating (<10% of the original value) is mainly from vapor radiation and conduction. The vapor cloud, therefore, significantly shields the originally exposed surface from the disrupting plasma. More than 80% of the incident plasma energy is, however, radiated from the tip of the hot vapor to the other adjacent components, as shown in Fig. 2.

Radiation from the vapor cloud is in the form of low-energy photons. The spectra of this radiation depends on the plasma power deposited and on the target material. Figure 3 shows the calculated photon spectra emitted from the front vapor regions of both C and Be primary target materials. Beryllium vapor emits harder photon spectra with significant line radiation because it has a much higher temperature than C vapor under the plasma conditions shown. Carbon vapor radiation is similar to W vapor radiation and is close to that of a blackbody for the stated conditions [5]. For higher incident plasma energy densities and low-Z target materials, most of the emitted photon radiation is in the form of line radiation. Therefore, a comprehensive treatment of line radiation and its transport is included in the A*THERMAL-S code [8].

The emitted radiation will strike nearby components, deposit its energy, and heat the components, thereby generating a secondary vapor cloud as shown schematically in Fig. 1. To evaluate the potential erosion losses due to such radiation, a nearby Be component such as a part with the divertor cassettes, a small blade, or a fin is analyzed. The secondary vapor cloud evolved above the exposed component surface will also shield its own surface from significant erosion if all the incident radiated energy is deposited at the surface. However, the shielding efficiency in this case is complicated by the expansion and diffusion of the secondary vapor across the magnetic field lines due to both classical and turbulent diffusion and to diffusion along magnetic field lines [7]. This vapor diffusion results in a decrease of the shielding layer away from the incident radiation, therefore allowing more power to reach the surface and cause more material erosion. In addition, as the secondary vapor expands above the surface, it occupies more volume and absorbs more primary radiation power from various sides of the cloud. This further heats the secondary vapor and its component, also increasing vapor losses and component erosion. More details of the model used in this analysis are published in Ref. 7.

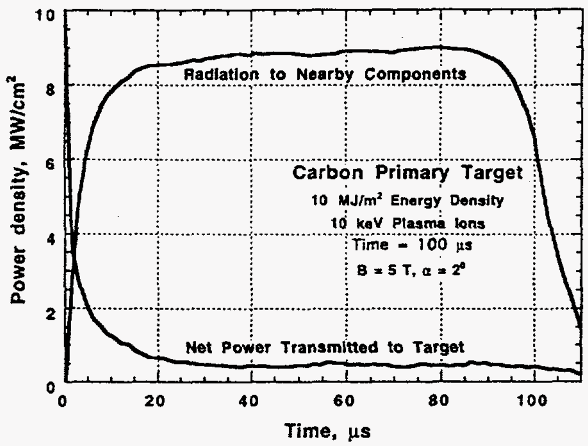

Figure 2. Power density to divertor target and nearby components during a disruption.

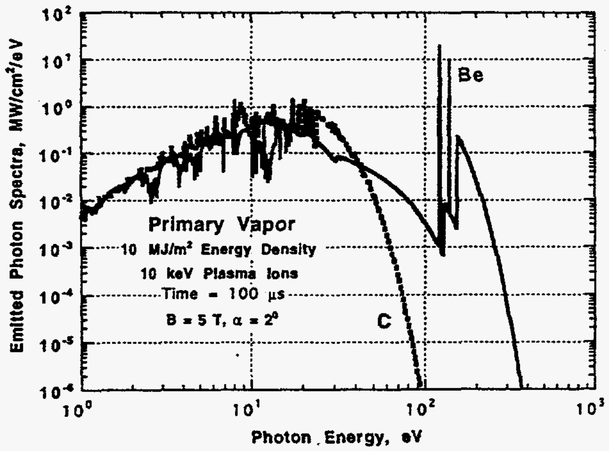

Figure 3. Photon radiation spectra emitted from primary vapor cloud.

Figure 4 compares vapor density and temperature of both primary and secondary beryllium vapor as a function of the normal distance to the exposed surface. The magnetic field lines are assumed to be parallel to the secondary target, as schematically shown in Fig. 1. The secondary vapor expands and accumulates up to only a few millimeters above the surface before it diffuses away from the incoming radiation. The primary vapor, however, expands toroidally for several meters against the incoming plasma and only about 10-50 cm normal to the surface due to diffusion across the field lines [5]. Because of the higher secondary vapor losses away from the incident radiation, the remaining vapor is more optically thin to incoming radiation and its temperature is lower than that of the primary vapor cloud. This results in much high vaporization losses of the nearby component compared than in the original disruption location, as shown in Fig. 5. Additional erosion of the resulting melt layer from splashing due to hydrodynamic instabilities and boiling (the SPLASH code) can further erode nearby metallic components and significantly reduce their lifetimes because of the much thicker melt layer relative to vaporization thickness [6].

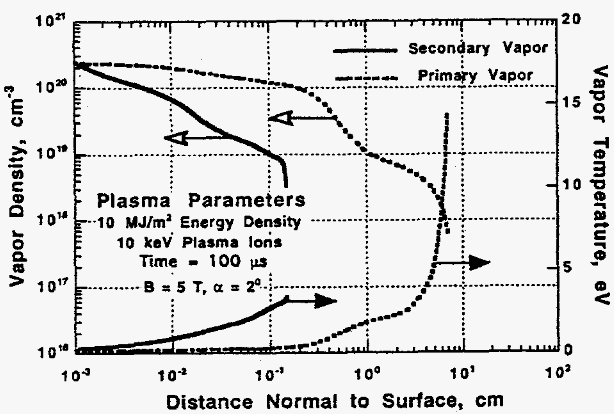

Figure 4. Vapor density and temperature of both primary and secondary vapor above surface.

3. CONCLUSIONS

Preliminary models and calculations to assess the erosion damage of nearby PFCs are presented. The intense radiation emitted from the primary vapor cloud during a thermal quench disruption can cause significant erosion of nearby components, particularly in closed divertor configurations such as the current ITER design. The secondary vapor cloud is not as effective as the primary cloud in protecting adjacent components due to strong vapor diffusion losses, vapor-cloud optical properties, and geometrical effects. More detailed analyses and more relevant experimental data are required to accurately predict lifetimes of plasma-facing and nearby components.

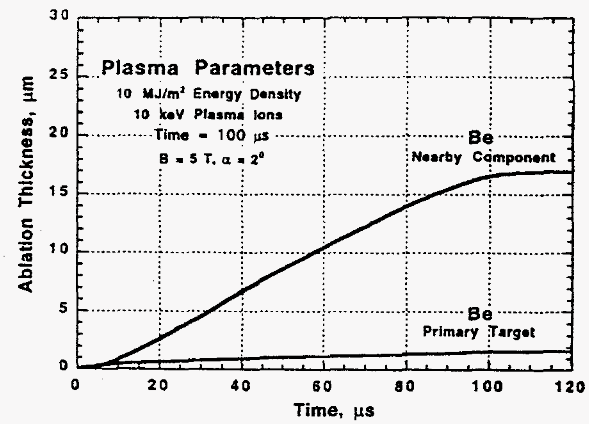

Figure 5. Vaporization losses of a beryllium primary and a beryllium nearby component.

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