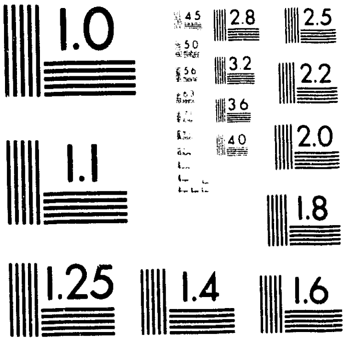
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# THERMAL ANALYSIS OF COATINGS AND SUBSTRATE MATERIALS DURING A DISRUPTION IN FUSION REACTORS*

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# Thermal analysis of coatings and substrate materials during a disruption in fusion reactors*

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## ABSTRACT

In a tokamak fusion reactor, the frequency of occurrence and the severity of a plasma disruption event will determine the lifetime of the plasma facing components. Disruptions are plasma instabilities which result in rapid loss of confinement and termination of plasma current. Intense energy fluxes to components like the first wall and the divertor plate are expected during the disruptions. This high energy deposition in short times may cause severe surface erosion of these components resulting from melting and vaporization. Coatings and tile materials are proposed to protect and maintain the integrity of the underneath structural materials from both erosion losses as well as from high thermal stresses encountered during a disruption. The coating thickness should be large enough to withstand both erosion losses and to reduce the temperature rise in the substrate structural material. The coating thickness should be minimized to enhance the structural integrity, to reduce potential problems from radioactivity, and to minimize materials cost.

Tile materials such as graphite and coating materials such as beryllium and tungsten on structural materials like copper, steel, and vanadium are analyzed and compared as potential divertor and first wall design options. The effect of the sprayed coating properties during the disruption is investigated. Porous sprayed material may be found to protect the structure better than condensed phase properties. The minimum coating thickness required to protect the structural material during disruption is discussed. The impact of self shielding effect by the eroded material on the response of both the tile/coating and the substrate is discussed.

## 1. INTRODUCTION

The performance of plasma facing components (PFCs) in magnetic fusion devices will be dictated to a large degree by their response to thermal loads generated from interactions with the plasma. The thermal loads are commonly divided into normal loads and off-normal loads. Normal loads are the power fluxes incident on the components during a typical discharge. These power fluxes determine the required basic parameters for the thermal design of these components. Off-normal events are those events that suddenly deliver high power loads in very short periods compared to the typical discharge. Examples of off-normal events are plasma disruptions, edge localized modes (ELMs) and runaway electrons. Plasma disruptions are considered one of the most serious events and can deliver thermal loads of the order of 10-20 $MJ/m^2$ over times of about 0.1 ms. In addition, plasma disruptions can generate severe eddy currents in PFCs which lead to large mechanical forces.

One key issue for a successful design and operation of a fusion reactor is a good understanding of the effects of plasma disruption on the PFCs such as the first wall and the divertor plates. The high energy fluxes expected on these components during a disruption will result in very high temperatures and severe surface erosion due to surface melting and vaporization. The choice of materials for PFCs is a major task. There are many material properties that dictate the component response and usefulness during normal and off-normal conditions; all of these properties must be considered. Some of the desirable properties include: high thermal conductivity, low Z, low sputtering, high melting point, low vapor pressure, and good thermal shock resistance. Since no single material can simultaneously satisfy all of the requirements, a coating or an armor material intended to face the plasma is bonded to or sprayed on a substrate material which provide structural support and cooling.

Coatings and tile materials are thus proposed as sacrificial layers to protect and maintain the integrity of the underneath structural materials. Coatings not only protect the structural materials from severe erosion, but also protect the structure from the high thermal stresses and temperatures encountered during the disruption which would severely limit the fatigue lifetime of these vital components.

Because of the expected frequency and severity of a disruption event, it is difficult to find a coating material with an adequate initial thickness to last the entire lifetime of the reactor. Therefore, it is proposed that for the next generation fusion reactors like ITER, to cover the surfaces of the plasma facing components by a thin layer of a metallic coating material such as beryllium or tungsten. This thin layer will have to be replenished periodically to substitute for the eroded material from

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disruptions and sputtering and maintain the structural integrity of the plasma facing components. It is much easier to replace the coating material by plasma spraying techniques or other methods than to replace the structural material which may require extensive repair and long reactor down time.

There are other proposed design options that use carbon based materials as tiles placed over the structural materials to provide the protection. Since it is difficult to continuously replenish the eroded carbon material by similar techniques available to metals, it is then required that the initial tile thickness be sufficient enough to protect the structure at the beginning-of-life (BOL) and near the end-of-life (EOL) operation. The end-of-life operation of a carbon tile should take into account the erosion (from disruption and both physical and chemical sputtering) as well as the neutron irradiation effect on the thermophysical properties. Reduced thickness and lower thermal conductivity of the tile material tend to increase the temperature rise and the thermal stresses in the substrate structure during disruptions.

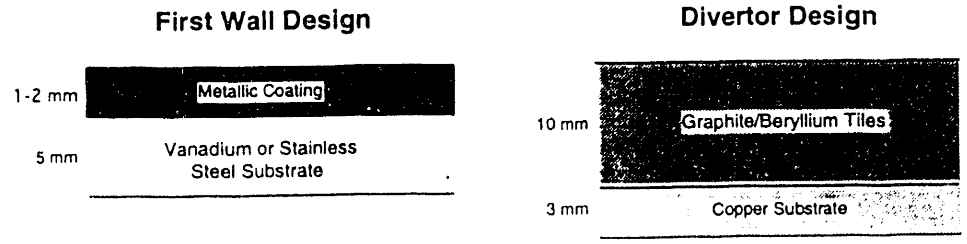
## 2. DESIGN OPTIONS AND PARAMETERS

The design parameters and options used in this analysis is shown in Fig. 1. Two design options are considered. One design option proposed for the first wall uses a thin metallic coating (beryllium or tungsten) of the order of a millimeter thick over a 5 mm thick stainless steel or vanadium structure. The other design option uses thick tiles (of the order of 1 cm) of carbon-fiber-composite (CFC) or beryllium over 3 mm thick copper alloy as the heat sink structure. This option is more suitable for the divertor plate where high heat loads and large erosion losses are expected. The CFC used in this analysis is the CX-2002 U composite which is available commercially. The end-of-life analysis assumes the thickness of the CFC to be eroded down to 3 mm, with a thermal conductivity similar to that of the irradiated SEPCARB. The effect of lower irradiated thermal conductivity such as similar to that of Nuclear Grade Graphite H451 is also analyzed.

**Disruption Effects on the Substrate Structure**

| Normal Operating Parameters | First Wall | Divertor |
|---|---|---|
| • Neutron wall loading | 2 MW/m$^2$ | 2 MW/m$^2$ |
| • Surface heat flux | 0.5 MW/m$^2$ | 5 MW/m$^2$ |
| • Coolant temperature | 300°C | 300°C |

| Disruption Parameters | First Wall | Divertor |
|---|---|---|
| • Energy density in thermal quench | 2 MJ/m$^2$ | 12 MJ/m$^2$ |
| • Energy density in current quench | 2 MJ/m$^2$ | 2 MJ/m$^2$ |
| • Thermal quench time | 0.1 ------------ 5.0 ms | |
| • Current quench time | 5 ------------ 20 ms | |



(Be or W Coating/Steel or Vanadium Structure) (Carbon or Beryllium Tiles/Copper Structure)

Fig. 1. Schematic illustrations of possible design options for the plasma facing components.

The disruption scenario is composed of two phases. A thermal quench phase followed immediately by a current quench phase. The duration of the thermal quench phase is usually short and it ranges from 0.1 ms to possibly 5.0 ms. The duration of the current quench phase is in the order of 5-20 ms. The energy densities deposited during the disruption considered in this analysis are typical of those estimated for the ITER design. During the thermal quench phase it is assumed that 2 MJ/m$^2$ is deposited on the first wall and 12 MJ/m$^2$ is deposited on the divertor plate. In the current quench phase, 2 MJ/m$^2$ is assumed deposited on both the first wall and the divertor plate.

The analysis presented in this paper is mainly devoted to studying the response of the substrate structural material to the combined two phase disruption[1]. The response of the tile and the coating materials to the disruptions has been analyzed in detail elsewhere[2-5]. The requirements for the coating and the tile thicknesses to maintain the thermal integrity of the substrate are investigated for various design options and disruption parameters.

## 3. MATERIALS RESPONSE

The thermal conditions of both the coating and the substrate materials prior to a disruption are calculated using the computer code HEATSS[6]. This code calculates the steady state temperatures distribution in a multi-layer structure subject to different initial and boundary conditions. Particle heat fluxes at the surface as well as volumetric energy deposition from neutrons are included in the code. Radiative boundary conditions at the surface and convective boundary conditions at the coolant interface as well as intermediate boundary conditions at the interface between each layer are also implemented in the code. The result of this calculation is used as an input for the disruption calculations.

The computer code A*THERMAL-2[7] is then used to calculate the thermal response of the multi-layer structure during the transient disruption event. The calculations are done with and without the effect of vapor shielding i.e., the shielding of the surface material by its own eroded material against the incoming plasma particles[9]. Vapor shielding may protect the PFCs by reducing the amount of energy that reaches the surface material during a disruption. Models used to evaluate vapor shielding effect are complicated and described elsewhere[8-10]. It is , however, believed that vapor shielding may be effective only during a severe thermal quench disruption with a duration much less than 1 ms. Longer disruption time will not allow the accumulation of the eroded vapor material in front of the incoming plasma particles to effectively shield the surface.

The analysis of the first wall design case where a thin metallic coating of beryllium (or tungsten) over a vanadium or a steel substrate is described below. Figure 2 shows the beryllium coating surface temperature as a function of time with and without the shielding effect for a combined 0.1 ms thermal quench followed by a 20 ms current quench. The shielding significantly reduces the coating surface temperature during the thermal quench. As a result, the net surface erosion is substantially reduced and in some cases more than an order of magnitude reduction in the erosion losses is achieved[9, 13]. However, the effect of vapor shielding during the thermal quench on the substrate temperature rise is found to be negligible mainly because the temperature rise in the substrate is largely due to the longer current quench phase. Figure 3 shows vanadium substrate temperature rise during a disruption with 0.5 mm tungsten coating. It can be seen that vapor shielding slightly reduces the maximum temperature rise. In the case of a beryllium coating the effect of the shielding is even less pronounced and in some cases the shielding slightly increases the temperature rise in the substrate. This is because vapor shielding reduces the energy lost in evaporating the surface and subsequently increases the energy conducted through the coating material to the substrate.

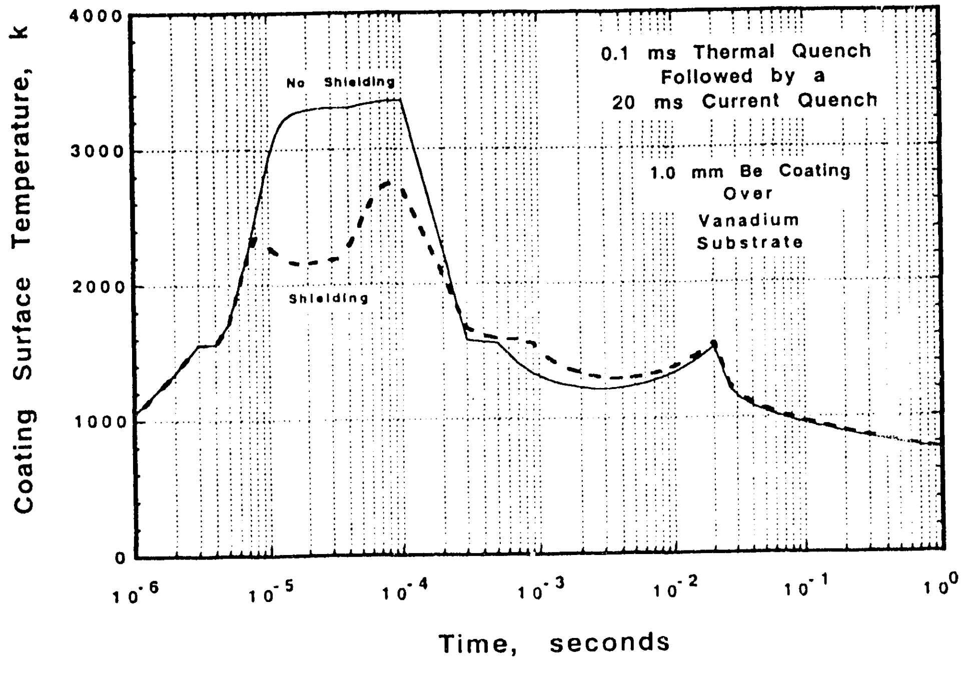


Fig. 2. Effect of vapor shielding on the coating thermal response to a disruption.

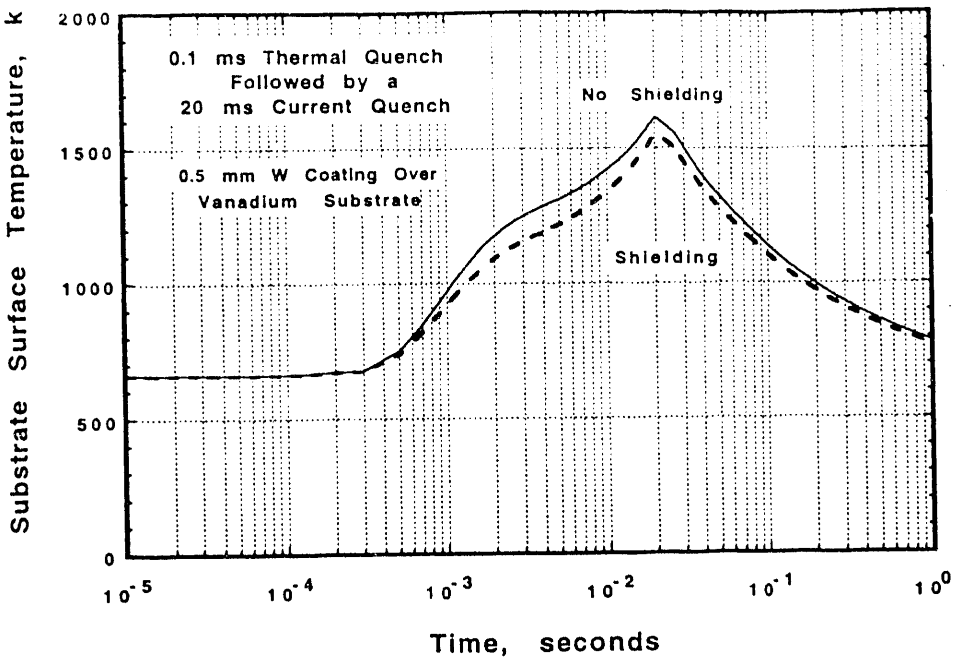


Fig. 3. Effect of vapor shielding during thermal quench disruption on vanadium substrate thermal response.

The effect of different coating thicknesses on the substrate temperature rise is shown in Fig. 4. Be coating thicknesses greater than 1 mm will reduce the maximum vanadium substrate temperature to less than 1000 k for the specified disruption scenario. Coating thickness should not be eroded below 0.5 mm in this case and it can be seen that a Be coating of 0.1 mm thick will entirely be in the liquid phase near the end of the current quench disruption. The loss of the entire coating due to melt layer instabilities or melt layer run-off may then cause substantial damage to the substrate structure[11, 12].

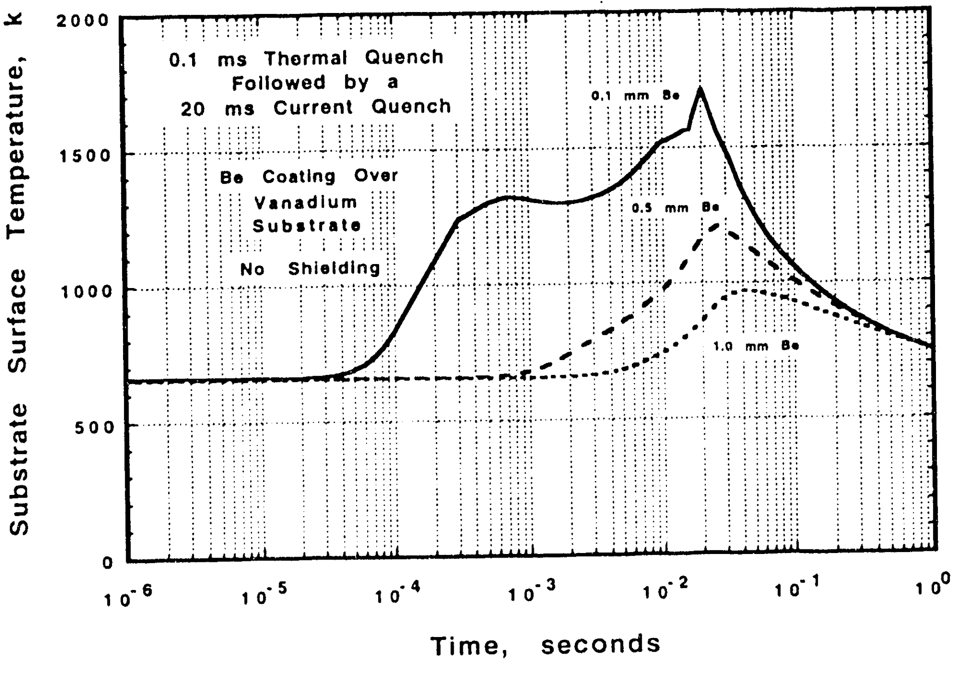


Fig. 4. Vanadium substrate temperature rise for different Be coating thicknesses.

Shorter current quench disruptions (< 20 ms) and longer thermal quench disruption (> .1 ms) will probably result in higher substrate temperature as opposed to shorter thermal quench and longer current quench disruption times. In general, longer disruption times allow less energy to go toward eroding the coating and more energy in conduction through the substrate material. Vanadium substrate temperature rise is somewhat lower than that for stainless steel for the same disruption and coating conditions.

The effect of using beryllium coating versus tungsten coating of the same thickness over stainless steel substrate along with the effect of the plasma sprayed material properties are shown in Fig. 5. Beryllium coating substantially reduces the substrate temperature rise during the disruption compared to the tungsten coating. Beryllium coating then offers a better protection to the substrate for the same coating thickness and disruption parameters. The main reason is that beryllium is less resistant to the disruption than tungsten. This means that more disruption energy will be spent in eroding beryllium than tungsten, leaving less energy to be conducted through the substrate. The better protection from the beryllium coating to the substrate is at the expense of a much higher beryllium erosion than tungsten. These disruption conditions happen to be less than the threshold required for any significant tungsten vaporization. Recoating by plasma spraying or other techniques will then be more frequently required in the case of beryllium. In addition, the cost of cleaning the redeposited material after disruption, safety considerations, and potential plasma contamination will be higher for the beryllium case. By the same analogy the degraded plasma sprayed properties of the coating (mainly the poor thermal conductivity) will even result in higher surface temperatures and subsequently more erosion in the case of Be. Therefore, more energy will be spent in eroding the coating and less energy will be conducted to the substrate causing lower temperature rise in the substrate. This means that the degraded plasma sprayed material properties may further protect the substrate from higher temperatures. However, in the case of tungsten the poor thermal conductivity of the plasma sprayed material will slightly increase the temperature rise in the substrate because most of the disruption energy is still conducted through the substrate since very little of this energy goes toward surface erosion.

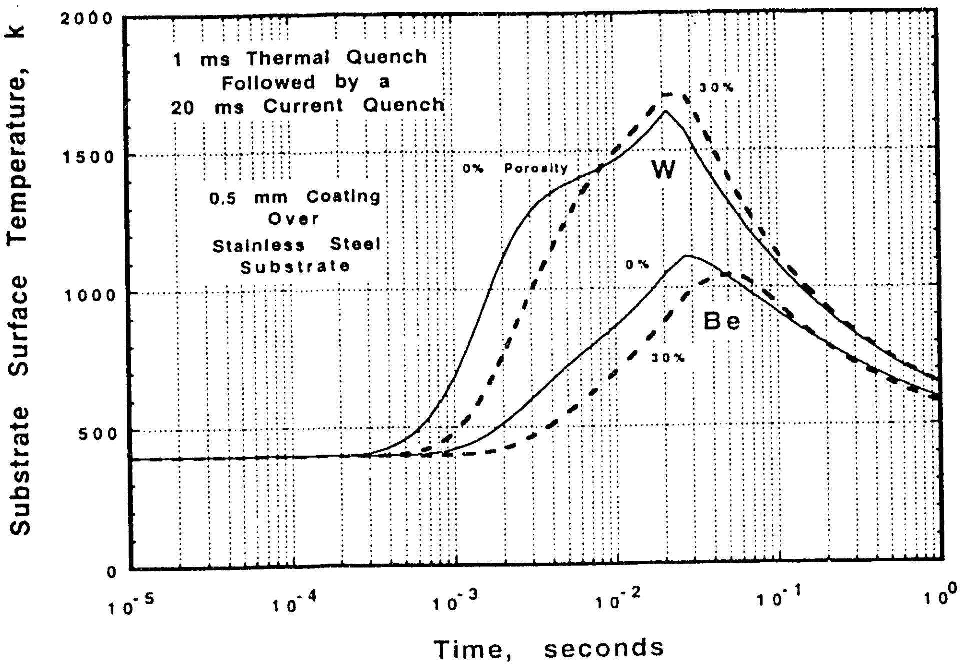


Fig. 5. Effect of porosity of plasma sprayed coating on steel substrate thermal response.

The analysis for the divertor design options, where thick graphite-based material or beryllium tiles are placed over a 3 mm copper substrate is presented below. Because graphite-based materials such as carbon-fiber-composites (CFC) can not be plasma sprayed, the initial tile thickness should be large (~ 1 cm) to compensate for the continuous sputtering and disruption erosion losses throughout the divertor lifetime[14]. It is expected, therefore, that the most severe conditions on the copper substrate will be near the end-of-life, where the tile thickness is eroded to its minimum and has suffered extensive neutron radiation damage to its thermophysical properties. For comparison purposes both beryllium and CFC (at EOL) tiles are assumed to be 3 mm thick on top of a 3 mm copper substrate. In addition, the thermal conductivity of CFC tiles at EOL is assumed similar to that of the irradiated SEPCARB material.

Figure 6 shows the copper substrate temperature rise for both CFC and Be tiles for the same typical disruption scenario. The calculation with the CFC tiles is done assuming two different irradiated thermal conductivities, i.e., irradiated SEPCARB and irradiated Nuclear Grade Graphite (H451) to show the effect of lower tile conductivity on the substrate response. The beryllium sprayed material is assumed to have 30% porosity and its conductivity is reduced by roughly a factor of two. The copper maximum temperature rise for both CFC (with SEPCARB conductivity) and beryllium tiles is roughly the same. However, lower thermal conductivity will result in much higher substrate temperature rise.

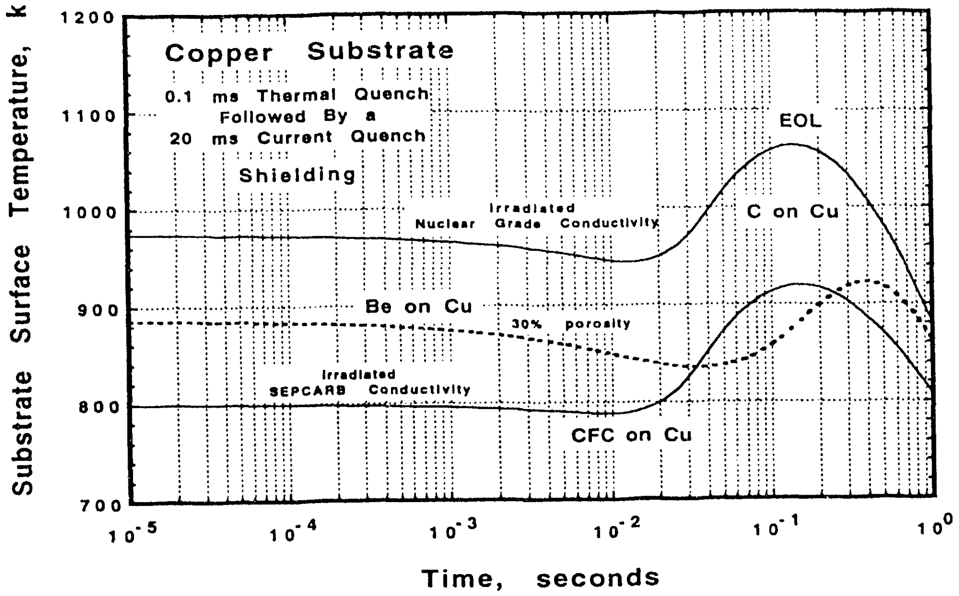


Fig. 6. Copper substrate temperature rise for different coating or tile materials.

Most of the above analysis assumed a short thermal quench disruption time (~ 0.1 ms). Longer thermal quench times (~ 5 ms) are feasible and although a longer disruption time is better from tiles erosion point of view, it can substantially increase the substrate temperature rise. Figure 7 shows copper substrate temperature response for two different thermal quench times when followed by a 20 ms current quench disruption. Possible repeated melting and solidification of the substrate surface may cause cracks and destroy the bonding at the interface with the coating which will lead to an accelerated erosion of the coating and a complete failure of both the coating and the substrate[13, 15].

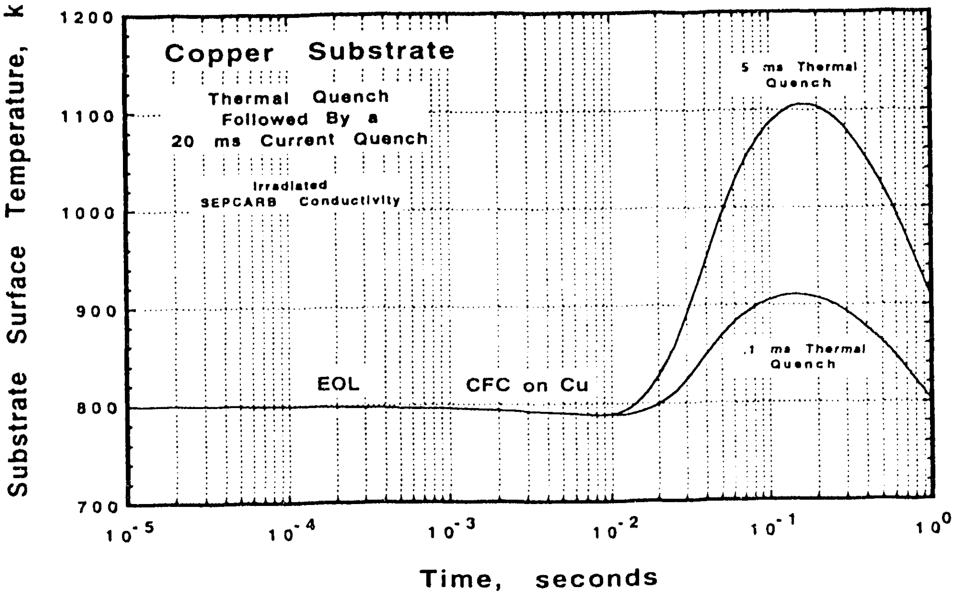


Fig. 7. Copper substrate temperature rise due to different thermal quench times.

## 4. CONCLUSION

Thermal analysis of the substrate structural materials is analyzed in detail during plasma disruptions using both HEATSS and A*THERMAL-2 computer codes. Tile and coating materials are essential to protect the structural materials from erosion and high temperatures and thermal stresses. The disruption time and the amount of energy deposited are key factors in determining the minimum coating or tile thickness required to protect the substrate. Vapor shielding may substantially reduce the coating or the tile erosion rate particularly at very short thermal quench disruptions. However, higher temperature rises in the substrate results from longer disruption times which will not be significantly affected by vapor shielding. Beryllium coating, in general, protects the substrate more effectively compared to tungsten coating for the same thickness and disruption conditions.

Porous sprayed coating material such as beryllium with lower thermal conductivity may be found to protect the substrate structure better than the full dense material depending on the disruption conditions. Adequate substrate performance during a disruption for a carbon tile design should be evaluated near the end-of-life where the tile thickness is at its minimum and the conductivity is at its lowest due to neutron radiation damage. In general, coating thickness should be minimized to reduce potential problems such as radioactivity, toxicity, cost, and plasma contamination.

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