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Thermal and Structural Limitations for Impurity-Control Components in FED/INTOR*

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Abstract

The successful operation of the impurity-control system of the FED/INTOR will depend to a large extent on the ability of its various components to withstand the imposed thermal and mechanical loads. The present paper explores the thermal and stress analyses aspects of the limiter and divertor operation of the FED/INTOR in its reference configuration. Three basic limitations governing the design of the limiter and the divertor are the maximum allowable metal temperature, the maximum allowable stress intensity and the allowable fatigue life of the structural material. Other important design limitations stemming from sputtering, evaporation, melting during disruptions, etc. are not considered in the present paper. The materials considered in the present analysis are a copper and a vanadium alloy for the structural material and graphite, beryllium, beryllium oxide, tungsten and silicon carbide for the coating or tile material.

1. Introduction

The successful operation of the impurity control system of the FED/INTOR [1, 2] depends to a large degree on the thermal and stress behavior of the components. This paper explores the thermal and stress aspects of limiter and divertor operation. The thermal analysis considers the temperature distributions in a flat, single-edged and a curved, double-edged limiter. The lower peak heat loads on the curved limiter result in lower operating temperatures through the limiter, and therefore the curved double-edged design is preferred. This design is used as the basis for a series of parametric calculations where the temperatures in a variety of plasma side materials are determined for a range of thicknesses.

The stress analysis utilizes the ASME code case N47 for class I components as a guide for the design. The peak stress levels and fatigue response of limiters and divertor plates are computed. Several geometric effects are considered, including the influence of the leading edge configuration compared to the front surface, the influence of tile thickness and width on the stresses in the heat sink, and influence of tile size on the bond stresses between the surface tiles and the heat sink.

2. Thermal Hydraulics

The first task of thermal hydraulics is to provide temperature distributions and to compare the advantages and disadvantages of a flat, single-edged bottom limiter with that of a curved, double-edged bottom limiter. The second task is to perform parametric analysis of the reference limiter and divertor, using an extensive set of parameters, including material selection, thickness, surface heat flux, thermal conductivity, and effect of irradiation.

2.1 Comparison Between Single- and Double-edged Limiters

The comparison between the flat and the curved limiters is divided into two parts, i.e., the top surface and the leading edge. The top surface is modelled by a two-dimensional slab geometry and the leading edge is modelled by a two-dimensional cylindrical geometry. The only difference in input to the thermal-hydraulic calculations for the flat and the curved limiters is the surface heat flux distribution. Only steady-state calculations are performed and compared. The surface heat flux distribution, used for flat limiter calculations, is shown in Figure 1. There are two peak heat fluxes along the top surface and one peak heat flux along the leading edge of the flat limiter. The maximum peak heat flux is approximately 4.3 MW/m^2 (based on a total heat rate of 80 MW). The surface heat flux distribution at the leading edge of the curved limiter is shown in Figure 2. The surface heat flux distribution was assumed conservatively to be constant (2.4 MW/m^2) along the top surface of the curved limiter.

Comparisons of the variation of maximum temperature in the structural material (copper) at the leading edge with coating thickness for different materials are shown in Figure 3. In all categories, the curved limiter operates at much lower temperatures than the flat limiter. This is a result of lower surface heat fluxes for the curved limiter both on the top surface and at the leading edge. One particular advantage of the curved limiter is that the copper temperature always remains below 200°C. The copper temperature in the top surface of the flat limiter is approximately 230°C and is close to the acceptable maximum temperature of copper. At the leading edge of the flat limiter, the copper temperature is even higher.

Thus, from a thermal-hydraulic point of view, the curved limiter is preferred in view of its lower operating temperatures for both the coating and the structural material.

2.2 Parametric Analysis of Limiter/Divertor

For these calculations, the heat sink structural thickness is assumed to be constant at 1.5 mm, and the contact conductance between the tile or coating and the structural material is assumed to be infinite, approximating the case for a braze joint. A constant heat flux of 2.4 MW/m^2 is used for the limiter and divertor top surface calculations, and a variable heat flux with a peak of 1 MW/m^2 is used for the leading edge calculations.

Figure 4 shows the maximum coating temperature vs. coating thickness for different coating materials on a copper substrate. With the exception of BeO, these temperatures would increase by 100 to 200°C for the case of a vanadium substrate. The surface temperature change for BeO with a vanadium substrate can be significantly higher because of the rapid change in the thermophysical properties with temperature. The high conductivity SiC proposed by the Japanese has the lowest surface temperature followed by tungsten and beryllium. Beryllium oxide has very high thermal conductivity at low temperatures, but the conductivity decreases rapidly with increasing temperatures. Hence, BeO at high thicknesses exhibits high temperatures. Conventional SiC and irradiated graphite exhibit the most rapid increase in temperature with coating thickness due to the relatively low thermal conductivities. It is important to note that radiation damage is known [3] to rapidly decrease the conductivity of non-metallic compounds. As the temperatures of the materials approach ~ 2000°C, the rate of temperature increase begins to slow due to enhanced radiation heat transfer.

Figure 5 shows the maximum structure (heat sink) temperature vs. coating thickness for different combinations of coating/structural materials at the top surface of the limiter. For relatively thin coatings (1 and 10 mm), the structure temperature increases slowly with the coating thickness and the maximum structure temperature is independent of the coating material on the top surface. Vanadium is always at higher temperatures than copper because of relatively poor thermal conductivity of vanadium. When the coating thickness is increased beyond 10 mm, the structural material temperature becomes dependent upon not only the coating thickness but also the coating material. This interesting behavior is the result of significant radiative heat transfer from the surface of the limiter/divertor to the first wall.

Figure 6 shows the maximum structure temperature vs. coating thickness for various combinations of coating/structural materials at the leading edge. The temperature behavior at the leading edge is quite different from that at the top surface. First, for relatively thin coatings (< 10 mm), there is a sharp increase in structural material temperature with increasing coating thickness. This is the result of a reduction in heat transfer area radially from the coating inward towards the coolant at the leading edge. This geometry effect does not exist at the flat top surface of the limiter where the structural temperature remains nearly constant with coating thickness. As the coating thickness is increased further, the previously described effect of radiative heat transfer becomes important for BeO-V, SiC-V, and SiC-Cu.

3. Stress Analysis

The primary purpose of the stress analysis is to ensure that the elastically computed maximum stresses in the structural material of the limiter/divertor are within the design allowables. The design allowables are determined by using the procedures of the ASME Boiler and Pressure Vessels Code, Section III. A second purpose of the analysis is to ascertain that the structural material has adequate fatigue life under the reference operating condition. The factors of safety for fatigue life calculation are identical to those used in the ASME Code.

The basic configuration of the leading edge for stress analysis is shown in Figure 7. Both the cooling and the heat sink structures are assumed to be linearly elastic. Because of rapid radiation hardening this assumption may not be unrealistic.

The coating is assumed to be segmented (Figure 8). For small coating thicknesses (~ 1 mm), the width of the coating is large compared to its thickness (Case I), and the full thickness of the coating is effective in exerting constraint on the substrate structure. However, when the coating thickness is large ($\geq$ 1 cm) so that its thickness is of the same order as its width (Case II), either the constraint of the coating on the substrate is ignored or the effective thickness (h_{eff}) of the coating is obtained by using a shear lag type analysis (see Figure 8).

Results show that even when the constraining effects of the coating on the substrate are ignored, a typical annealed copper does not have sufficient strength to meet the ASME code criteria for any reasonable thickness of coating considered. However, beryllium copper which is a much stronger alloy of copper can meet the code requirements in all cases.

A similar comparison, when vanadium (V-15Cr-5Ti) is used as the structural material, shows that vanadium can meet the code requirements for up to ~ 2 cm thick coating.

The fatigue analysis shows that a vanadium alloy (V-15Cr-5Ti) without any constraint from the coating will be adequate up to a coating thickness of 2 cms. However, such is not the case with annealed copper. The poor performance of annealed copper inspite of its superior thermal conductivity as compared to vanadium is unexpected. A close examination of the stress analysis shows that although the stresses due to the temperature gradient through the thickness of the heat sink structure is significantly higher in the case of vanadium than in the case of copper, the major component of the total stress being caused by the toroidal constraint of the cooler central region of the limiter on the hot-front wall is almost identical for the two materials. Consequently, the superior performance of the vanadium limiter is a reflection of its superior strength, and fatigue properties.

The stress and fatigue analyses provided above are based on the assumption that the coating provides no constraint on the substrate. This is a valid assumption provided the coating is extensively cracked due to stresses during operation. If, on the other hand, the coating is not extensively cracked, then it will exert some constraint on the substrate dependent on its thickness and segment width. It is assumed in the present analysis that the coating (or tile) consists of square segments that are perfectly bonded to the underlying substrate. The results show that the effect of the constraint of the coating is to raise the stresses at the top surface and reduce the stresses at the leading edge. As a result, vanadium can meet the code criteria for a thickness of coating of up to 3 cm. The inclusion of the coating constraint in the analysis can substantially change the relative performance of the coating material and also transfer the critical location for fatigue from the leading edge to the top surface of the limiter. In general, the fatigue lives also depend on the width of the tile. Figure 9 shows the maximum allowable tile width for a given tile thickness or conversely, the maximum allowable tile thickness for a given tile width, corresponding to a minimum fatigue life of 10^5 cycles of a vanadium substrate. For thicknesses less than 1 cm, all three materials can have any tile width without violating the fatigue life requirement.

Braze shear stresses following the braze cycle process are evaluated for various combinations of tile and substrate materials. To be realistic, a higher braze temperature (960°C) is assumed for tungsten than for the other materials (600°C).

Shown in Figure 10 are combinations of tile length and thickness which result in stresses of 70 MPa (10 ksi). These plots indicate that beryllium brazed to copper and beryllium oxide brazed to vanadium appear to have the greatest potential for having relatively large tiles. Silicon carbide and beryllium brazed to vanadium appear to be viable for tile sizes of approximately 4.0 cm.

4. Conclusions

As a result of lower surface heat flux on the curved limiter, it operates at a much lower temperature than a flat limiter.

Both vanadium and copper operate at fairly low temperatures and are acceptable from a thermal viewpoint. However, from a stress and fatigue viewpoint annealed copper is too weak and a stronger alloy such as beryllium copper or a vanadium alloy is acceptable.

Allowable coating thickness and width depend on the coating material as well as the structural material. However, the maximum braze shear stress during cooldown will also have to be considered in the design.

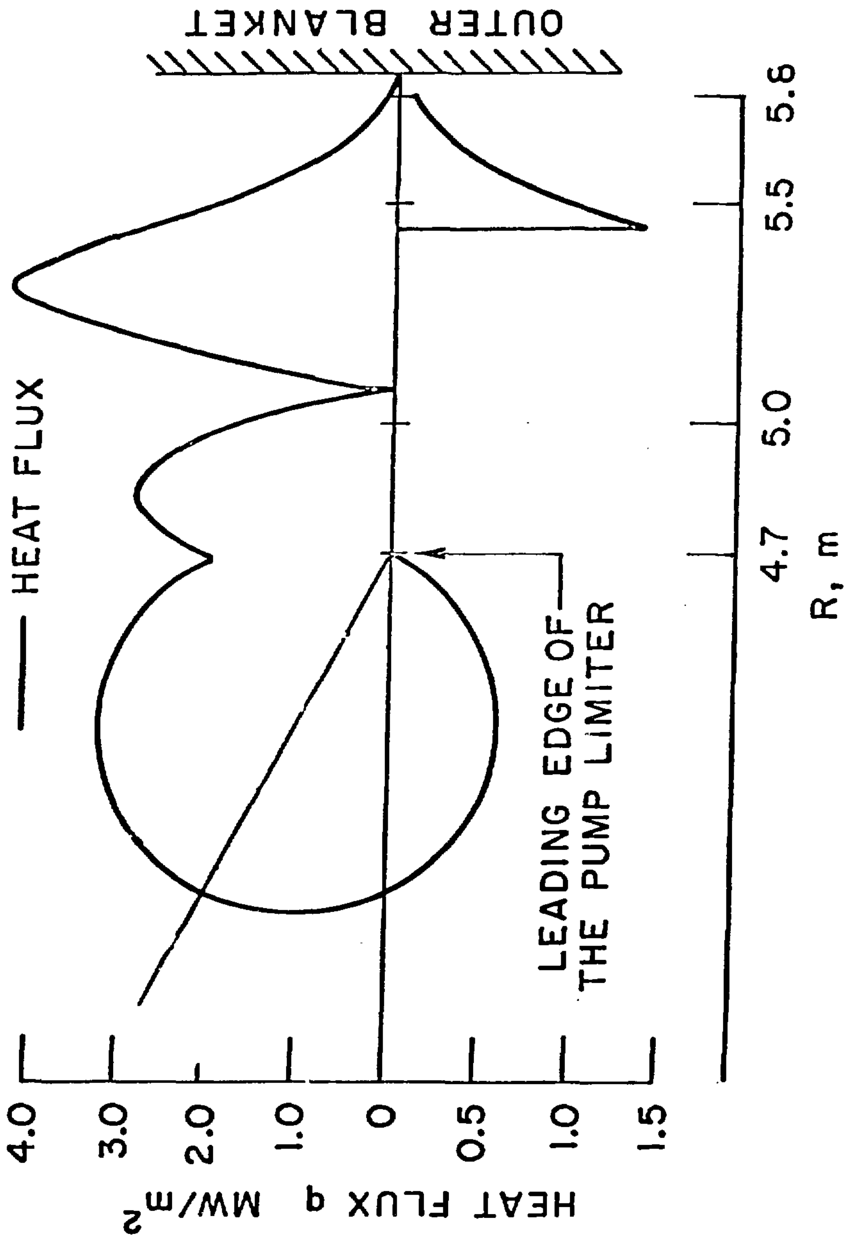
References

[1] STACEY, JR., W. M., et al., "The US Contribution to the International Tokamak Reactor Phase-I Workshop," INTOR/81-1 (1981).

[2] STACEY, JR., W. M., et al., "The US FED/INTOR Activity and US Contribution to the International Tokamak Reactor Phase-II Workshop," FED-INTOR/82-1.

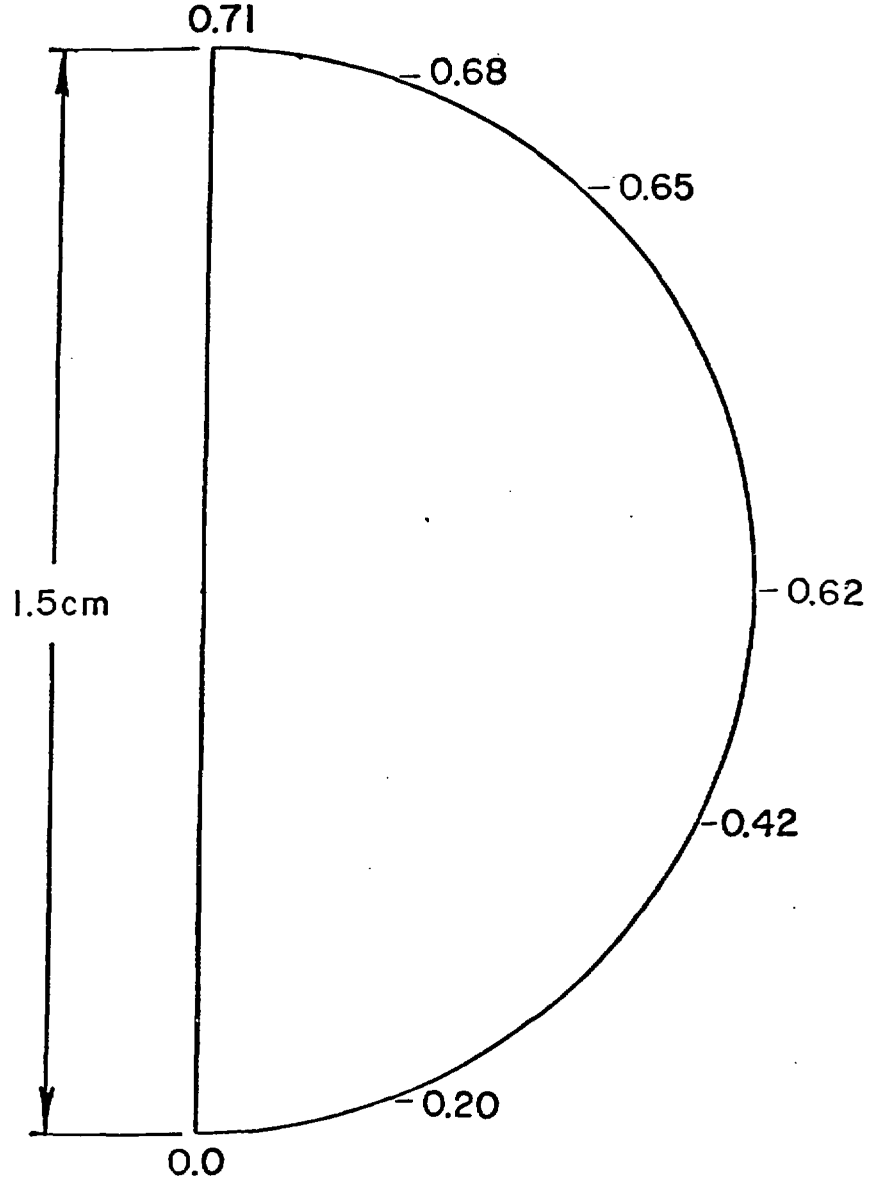
[3] ABDOU, M. A., et al., "Impurity Control and First Wall Engineering," FED-INTOR/ICFW/82-17, Chapter VII, p. 81 (1982).

List of Figures

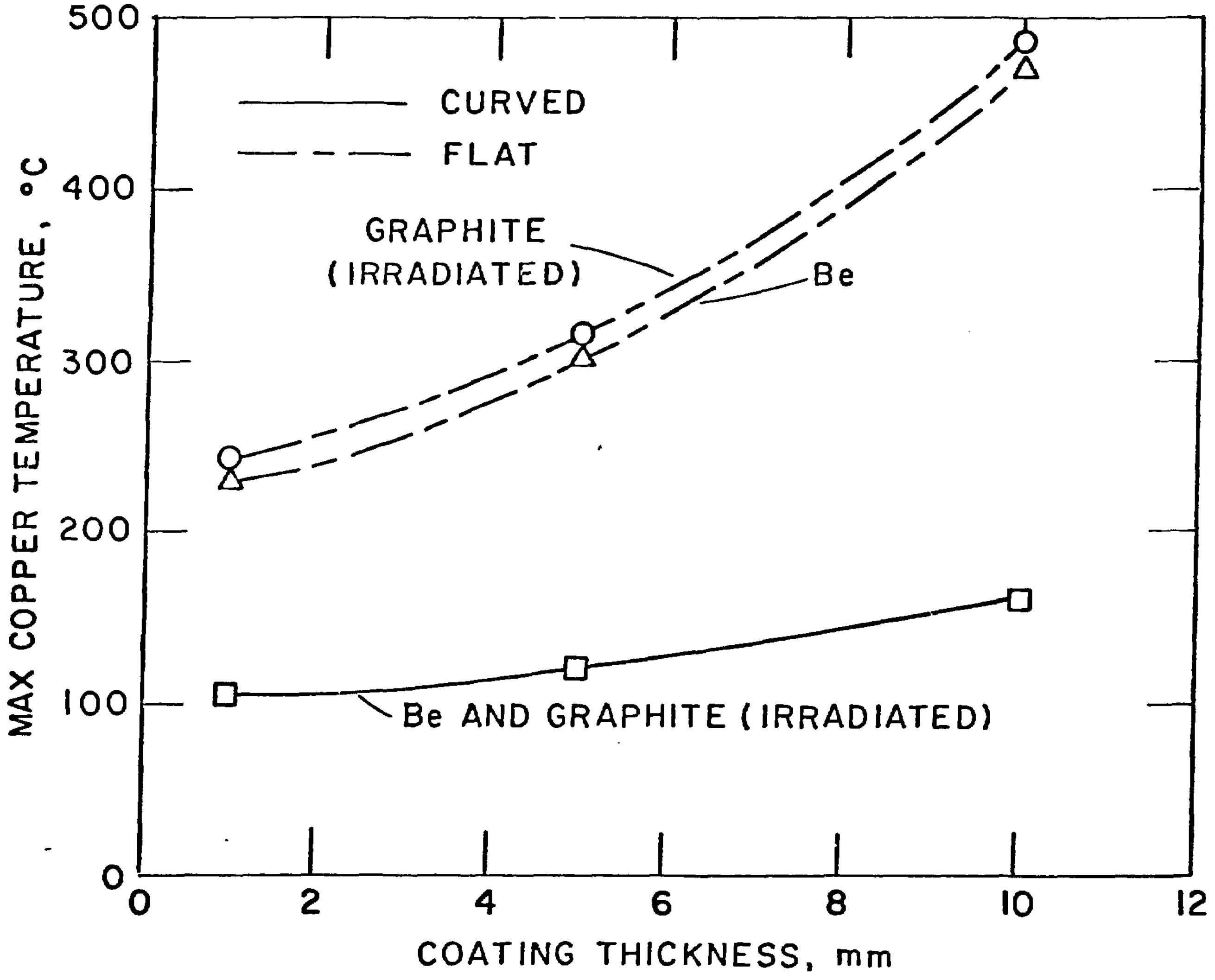


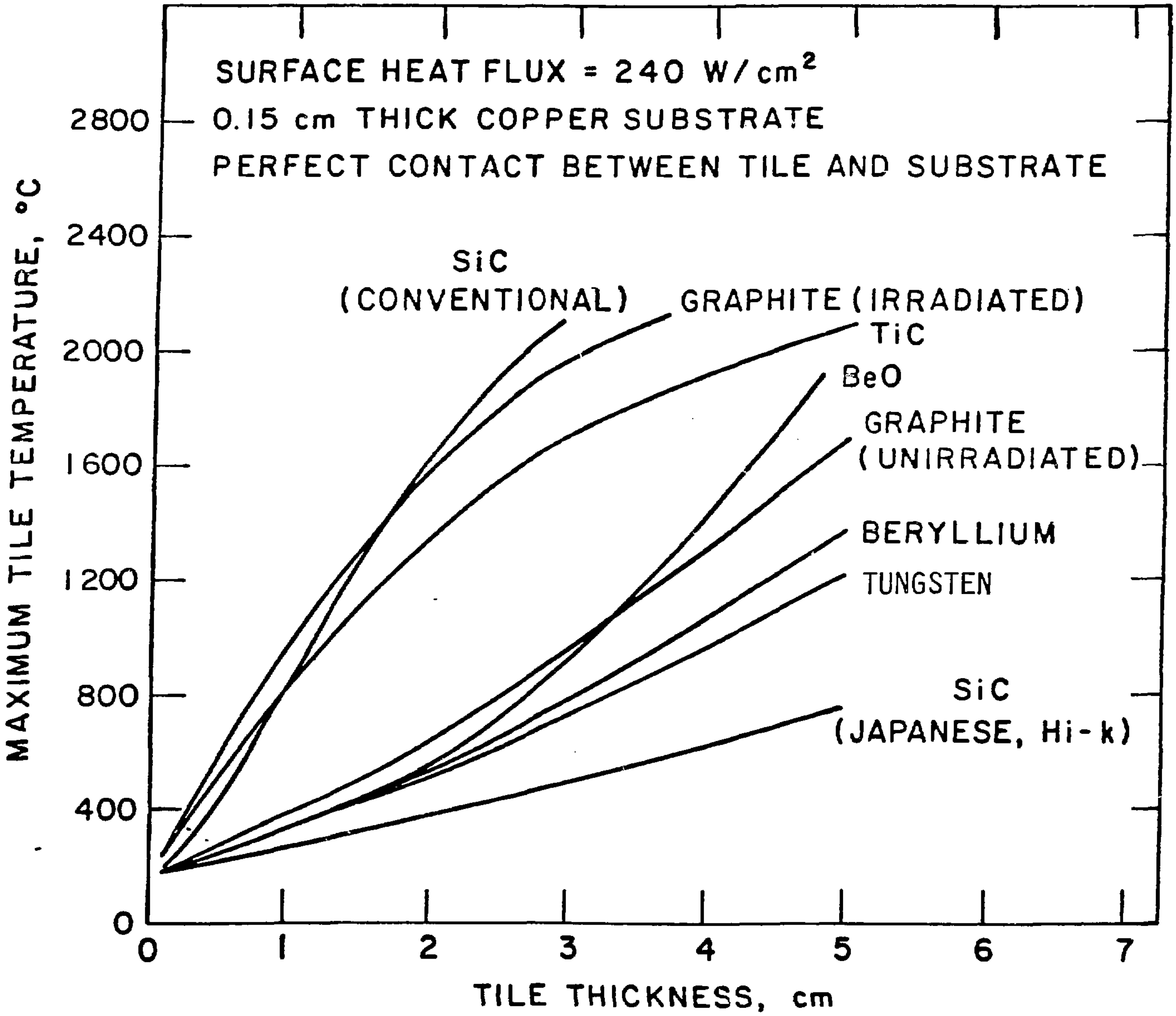
HEAT FLUX
OUTER BLANKET
LEADING EDGE OF THE PUMP LIMITER
HEAT FLUX q MW/m²
4.0
3.0
2.0
1.0
0
0.5
1.0
1.5
4.7
5.0
5.5
5.6
R, m

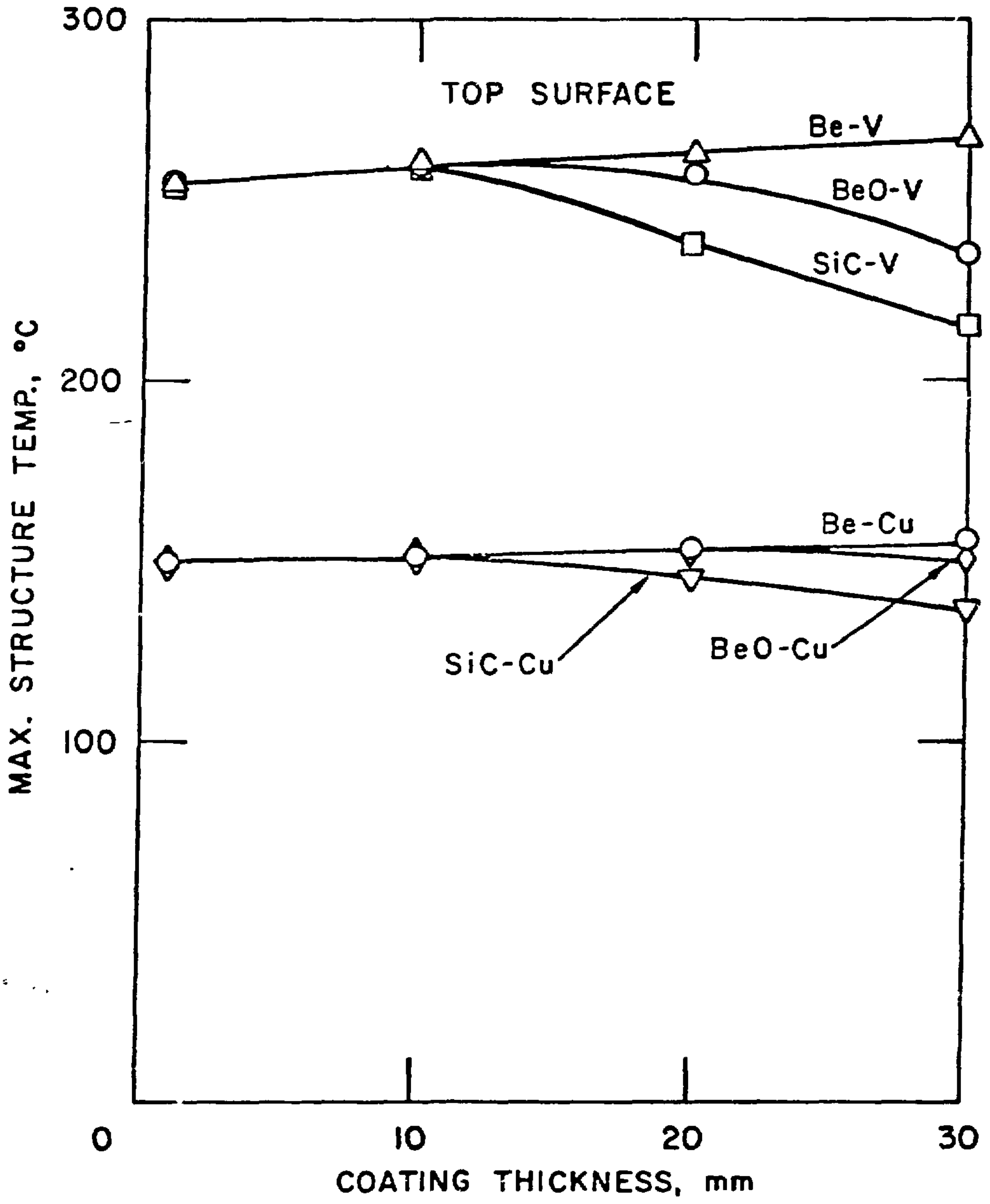
LEADING EDGE HEAT FLUX (MW/m^2)
CURVED LIMITER



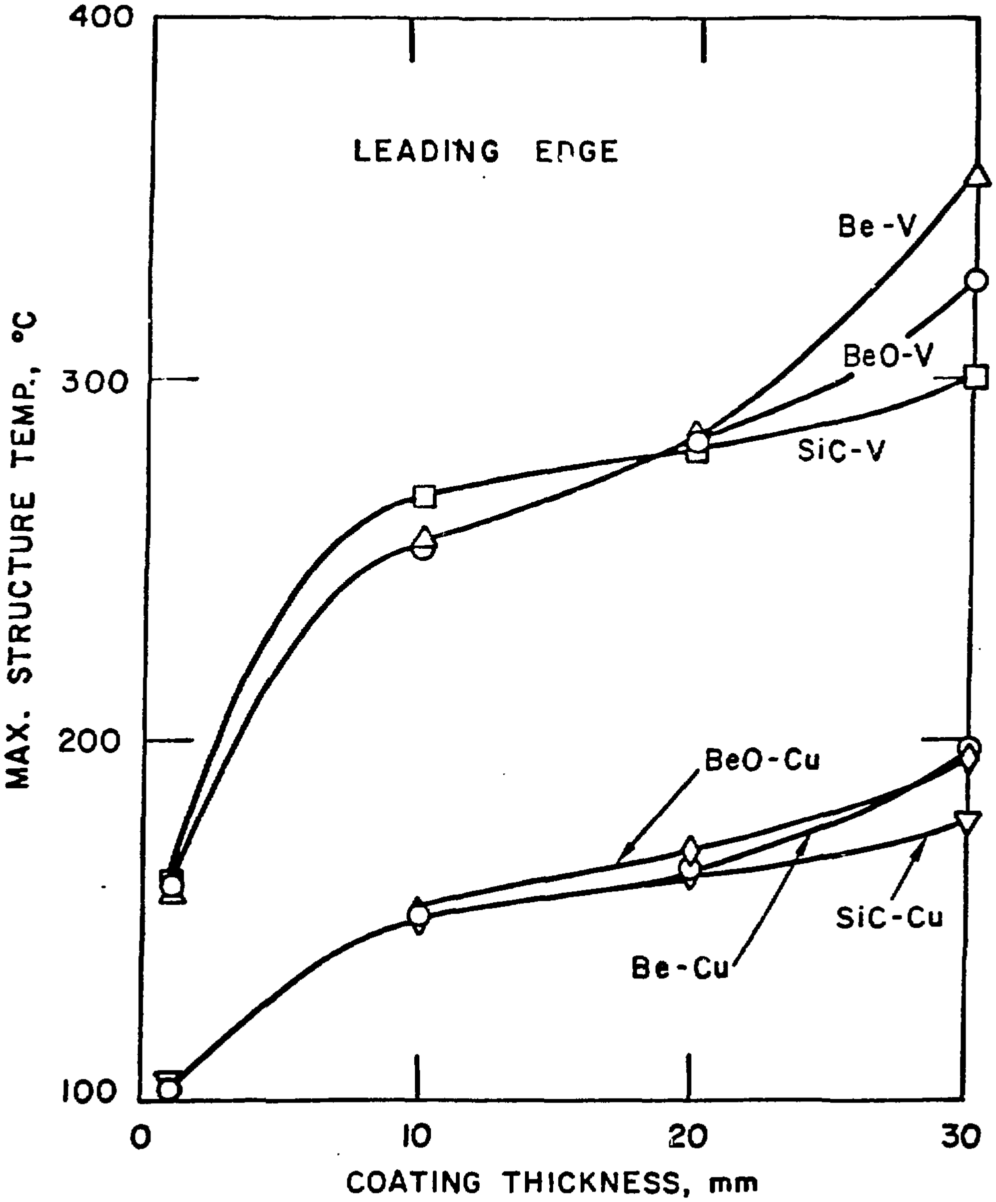
CURVED LIMITER

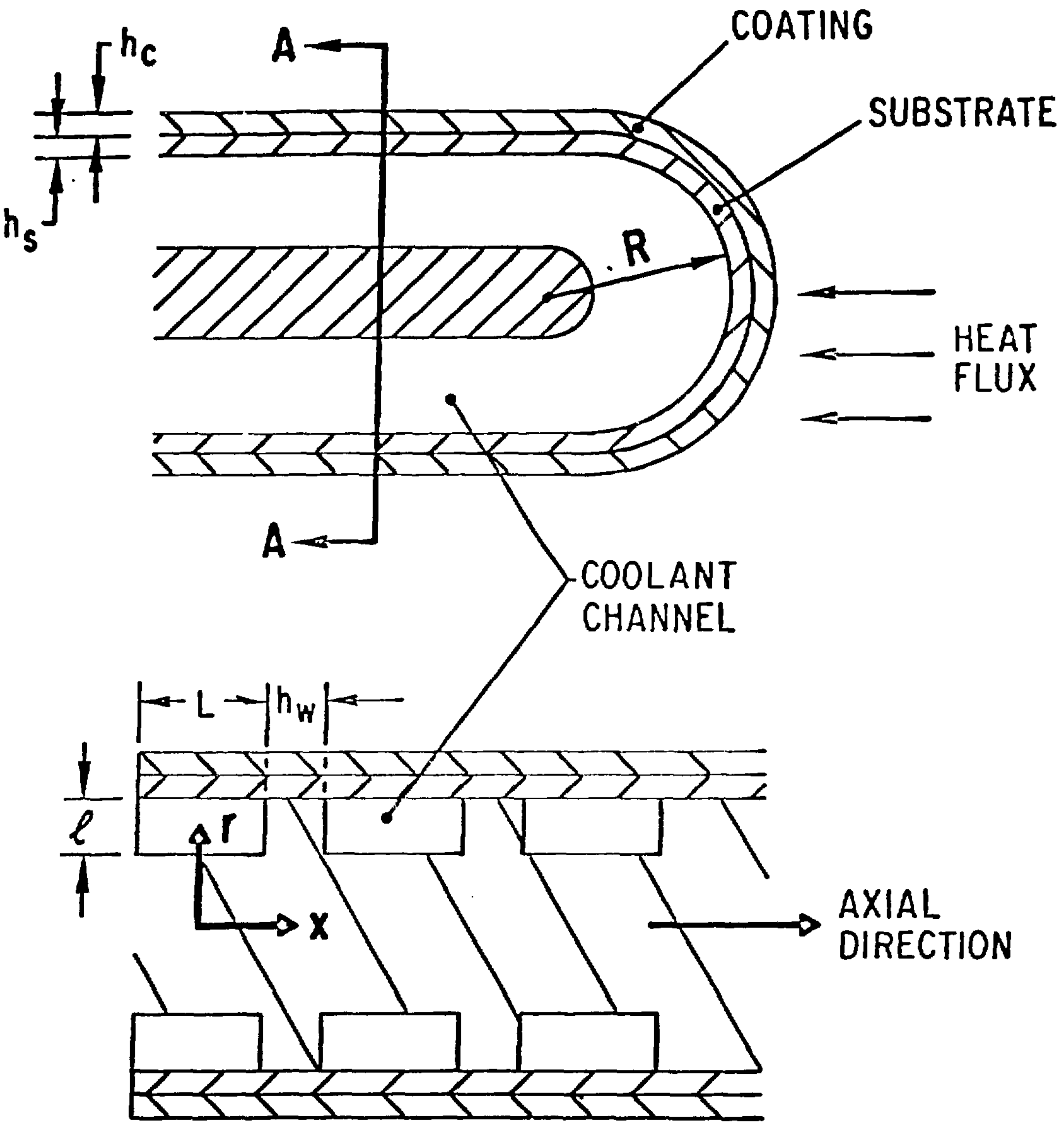

CURVED
FLAT
GRAPHITE (IRRADIATED)
Be
Be AND GRAPHITE (IRRADIATED)
MAX COPPER TEMPERATURE, °C
0
100
200
300
400
500
0
2
4
6
8
10
12
COATING THICKNESS, mm


SURFACE HEAT FLUX = 240 W/cm²
0.15 cm THICK COPPER SUBSTRATE
PERFECT CONTACT BETWEEN TILE AND SUBSTRATE
SiC (CONVENTIONAL)
GRAPHITE (IRRADIATED)
TiC
BeO
GRAPHITE (UNIRRADIATED)
BERYLLIUM
TUNGSTEN
SiC (JAPANESE, Hi-k)
MAXIMUM TILE TEMPERATURE, °C
0
400
800
1200
1600
2000
2400
2800
TILE THICKNESS, cm
0
1
2
3
4
5
6
7

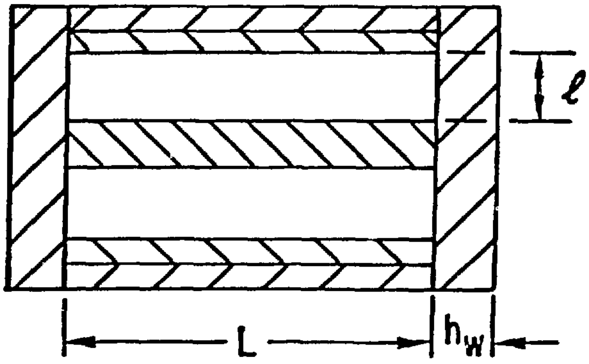


TOP SURFACE
Be-V
BeO-V
SiC-V
Be-Cu
SiC-Cu
BeO-Cu
300
200
100
0
10
20
30
MAX. STRUCTURE TEMP., °C
COATING THICKNESS, mm

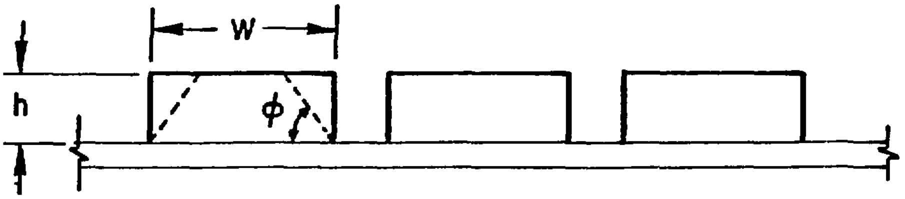

LEADING EDGE
Be-V
BeO-V
SiC-V
BeO-Cu
SiC-Cu
Be-Cu
MAX. STRUCTURE TEMP., °C
400
300
200
100
0
10
20
30
COATING THICKNESS, mm


h_c
h_s
A
A
COATING
SUBSTRATE
R
HEAT FLUX
COOLANT CHANNEL
L
h_w
ℓ
r
x
AXIAL DIRECTION

VIEW A-A

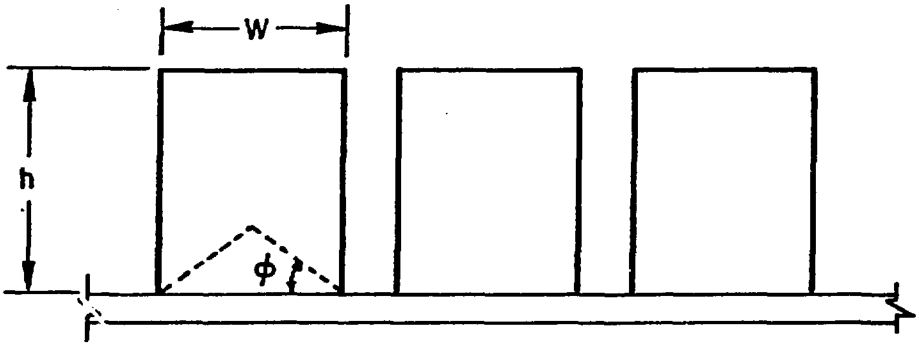

ℓ
L
h_w

CASE I $h \leq \frac{W}{2} \tan \phi$

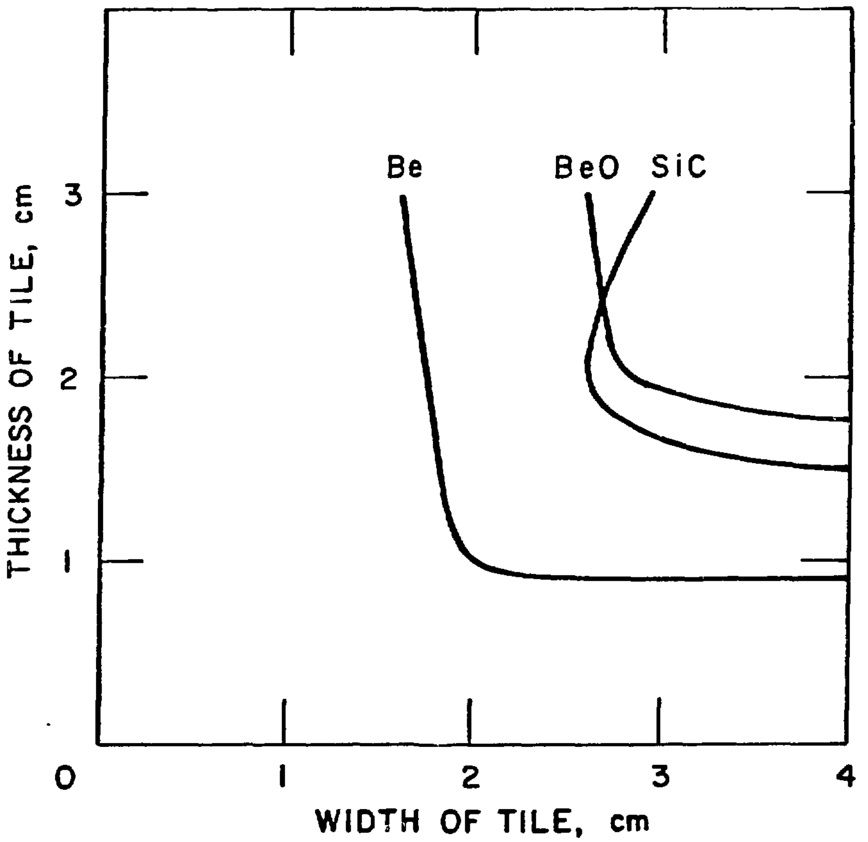


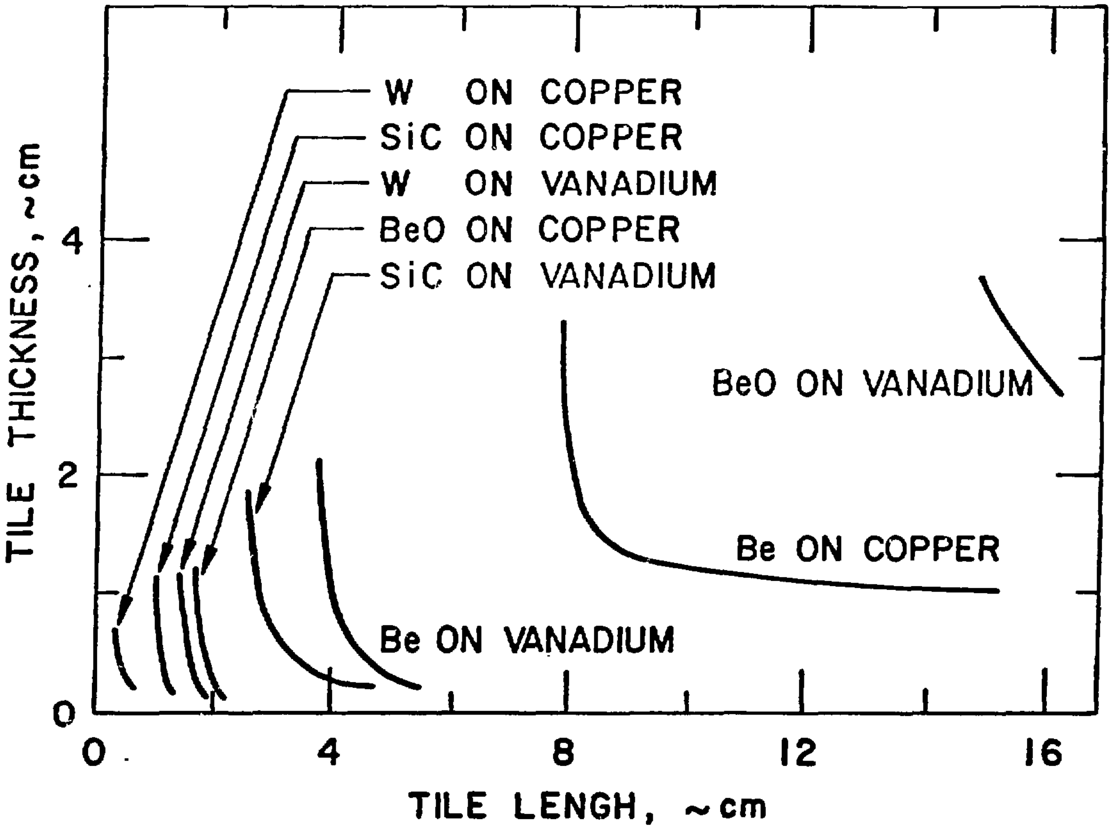
$$h_{eff} = h \left[1 - \frac{h}{W} \cot \phi \right]$$

CASE II $h > \frac{W}{2} \tan \phi$



$$h_{eff} = \frac{W}{4} \tan \phi$$


Be
BeO
SiC
THICKNESS OF TILE, cm
3
2
1
0
1
2
3
4
WIDTH OF TILE, cm


W ON COPPER
SiC ON COPPER
W ON VANADIUM
BeO ON COPPER
SiC ON VANADIUM
BeO ON VANADIUM
Be ON COPPER
Be ON VANADIUM
TILE THICKNESS, ~cm
0
2
4
0
4
8
12
16
TILE LENGH, ~cm