ERRATA

The penultimate sentence on page 4 is incorrect and requires clarification. It should read:

"For design purposes, we note here that with internal heat generation and a given heat flux, the temperature rise in the metal would be half as much as the temperature rise with surface heating."

This statement is simply derived from the heat conduction equation:

\[
\frac{\partial^2 t}{\partial x^2} + \frac{q}{k} = 0
\]

\( q \) = uniform internal heat generation per unit volume
\( q = q_l = \text{heat flux} \)
\( t \) = temperature difference
\( k \) = thermal conductivity
\( l \) = plate thickness

a) Heat transfer at one face only:

\[
\frac{\partial t(0)}{\partial x} = t(l) = 0
\]

\[
t = \frac{q}{2k} \left( l^2 - x^2 \right)
\]

\[
t_{\text{max} @ (x=0)} = \frac{ql^2}{2k} = \frac{q l}{2k}
\]
b) Heat transfer at both faces:

\[ t(0) = t(l) = 0 \]

\[ t = \frac{q x}{2k} (l-x) \]

\[ t_{\text{max}} @ (x = \frac{l}{2}) = \frac{q l^2}{8k} = \frac{q l}{2k} \]

c) No heat generation

\[ \frac{\partial t}{\partial x} = \frac{-q}{k} \]

\[ t = \frac{q (l-x)}{k} \]

\[ t_{\text{max}} @ (x=0) = \frac{q l}{k} \]
HEAT TRANSFER TESTS ON A SPOT HEATED, WATER-COOLED TUNGSTEN PLATE

The plate was a 2" diameter by 1/8" thick "Kennametal" disc brazed into a 6" square by 1/8" thick copper plate. The plate was heated by bombardment by 15 keV electrons from a 0.016" tungsten filament wound into a 7/16" diameter spiral. The target was cooled by water flowing in a 2.5" wide by 0.193" passage. The gross heat input was varied from 0 to 6 kW. The flow rate was varied between 0.7 fps to 12 fps. Maximum heat flux was approximately 4.2 kW/cm².

Kennametal is sintered tungsten consisting of 90% tungsten, 7 1/2 % nickel and 2 1/2 % copper with a melting point of 3450°C (6250°F) and a conductivity of 0.183 cal/sec°C cm. Figure 1 shows the microscopic "sintered" appearance of the metal prior to testing. Tool marks from the lathe facing operation were also clearly visible.

Test No. 1: The target was subjected to a gross power input from 0.45 kW to 2.9 kW during a period of 3.3 hours with a water flow of 4.6 fps and water temperature of about 20°C. The plate started to tarnish almost as soon as the power was turned on. Boiling was observed in form of small rapidly disappearing bubbles. The test was stopped because the filament had arced over to the target.

Figure 2 shows the microscopic appearance of the metal in the vicinity of the boiling after the test. The "sintered" character of the surface was destroyed and the surface showed 10 microns deep pits. The tool marks were partially obliterated. The metal appearance far from the boiling region and on the beam side of the plate remained unchanged.

Test No. 2: The plate was installed and subjected to a gross power input of 1.5 kW for 10 hours. The plate had tarnished uniformly while it was exposed to the air. Shiny spots appeared on the plate at the bubble nucleation centers
as soon as the test was restarted. After 10 hours the tool marks were practically obliterated. The power was increased to 3.9 kW in a period of 2 hours. The test was stopped when the character of boiling changed. There was a sudden appearance of a small unstable "film" spot.

The target was again examined under the microscope. There was not much change in the appearance of the metal except for the fact that some of the pits had increased to 25 microns deep. The surface on the beam side was still unchanged.

**Test No. 3:** A thermocouple was installed in a 0.016" diameter by 0.015" deep hole on the water side of the plate. At first it was impossible to record a metal temperature. The recorded temperature never exceeded 100° C. Finally, some approximation of the metal temperature was registered as a result of imbedding the thermocouple in indium.

Tests were made with gross power inputs from 2.9 kW to 3.7 kW and water flows from 1.6 fps to 10.6 fps. The results are shown on Figure 4A. As a result of these tests, a number of "burn-out" points were identified.

The thermocouple was swept out of the hole during one of the higher velocity test runs. Subsequent attempts to record a metal temperature were futile. The tests made thereafter were based on visual evidence.

At each given power level above 3.3 kW the following pattern was observed as the flow was decreased. At first a small, unstable spot of "film" boiling appeared. The spot then grew as the flow was decreased until a large stable "film" spot suddenly appeared. This spot did not grow appreciably as the flow was decreased. Finally, a red spot would appear at the center of the heated zone. At the higher power inputs, the red spot appeared simultaneously with the larger stable "film" spot. When the flow was increased, the red spot would gradually disappear but the large "film" spot persisted until the flow was considerably higher than when the large spot appeared. Finally at a given flow the large spot disappeared leaving no trace of the smaller unstable spot.

The tests were concluded when the vacuum, on the beam side of the target, was destroyed after reaching a burn-out point.
For the purpose of these tests, burn-out is defined by the appearance of the red spot. The results are shown on Figure 4B.

Under the microscope, the water side of the plate showed continued deterioration. The pits were about 3µ microns deep.

The appearance of the beam side of the plate is shown on Figure 3. A crack had developed at the center of the hot spot and the "sintered" appearance was destroyed. The depth of the crack was at least 260 microns deep. The target was no longer vacuum tight.

Discussion and Conclusions

1. Erosion-Corrosion

Previous tests on aluminum and copper have indicated that cavitation attack is to be expected at high heat fluxes. The tarnishing and subsequent bright spots on the tungsten target seem to indicate an additional chemical attack (probably due to oxidation). The tests lasted a total of 56 hours giving a corrosion rate of 2.5 mils/100 hours even at moderate power levels. It is possible that removal of oxygen from the water may decrease this corrosion rate. Hard chrome plating of the water side of the plate, if possible, would probably remedy the corrosion problem entirely.

2. Maximum Heat Flux

For estimating purposes we may assume that there is no radial heat conduction in the plate and the maximum heat flux, ignoring the resistance of heat transfer to the water, would be:

\[ q_{\text{max}} = \frac{k_1 \Delta T}{t} \]

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\[ q_{\text{max}} = \text{maximum heat flux, watts/cm}^2 \]
\[ k = \text{conductivity, } 0.183 \text{ cal/sec cm}^0 \text{ C} \]
\[ T_m = \text{metal melting point, } 3474^\circ \text{ C} \]
\[ T_w = \text{water temperature, } 20^\circ \text{ C} \]
\[ t = \text{metal thickness, } 0.318 \]
\[ q_{\text{max}} = \frac{(4.18)(0.183)(3474)}{0.318} = 8.26 \text{ kW/cm}^2 \]

It is, however, impossible to achieve this heat flux due to the thermal resistance at the metal-water interface. The limiting heat flux is frequently called the burn-out flux. (See TN-63-64, "Boiling Heat Transfer Peak Heat Fluxes - Jurav for further discussion of burn-out heat fluxes.)

Previous tests have shown that approximately 75% of the gross power input on this test apparatus is transmitted through the test plate. Since the filament area is approximately one square centimeter, the data given on Figure 48 may be used for design purposes after applying the correction factor of 0.75.

It should be noted that these tests were made with a bulk water temperature of 20\(^\circ\) C. Previous tests on copper plates have shown that the metal temperature is very sensitive to the water temperature. At 5 kW, an increase in water temperature from 20\(^\circ\) C to 67\(^\circ\) C resulted in an increase of metal temperature from 170\(^\circ\) C to 260\(^\circ\) C.

For design purposes, we note here that the heat flux for a plate with internal heat generation is eight times the heat flux for a surface heated plate with the same temperature difference.

I acknowledge gratitude to Ed. Garwin for his helpful discussions.
Fig. 1  Water Side Prior to Testing.  
X 560

Fig. 2  Water Side After Test.  
X 560
Fig. 3  Beam Side After Final Test.
X 140