## Thermal Diffusivity of Nickel from 25° to 500°C*†

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THE thermal diffusivity of nickel from 25° to 500°C has been measured by extending the pulse technique developed by Woisard[1] to higher temperatures.

Any measurement of thermal diffusivity assumes that this parameter remains constant during a slight temperature variation. If it is assumed that the thermal diffusivity is constant over a temperature range of 10°C, the transient character of the heat flow of the pulse technique allows measurements to be taken while the ambient temperature is slowly increased. The experiment was conducted under this assumption and measurements over a wide temperature range were taken quite rapidly; a typical furnace cycle being about 12 h.

A heat pulse was generated at one end of the sample rod by discharging a capacitor bank across the circuit containing the sample rod and a small silicon carbide heater. The resulting heat flow closely approximated that of a delta function heat input at one end of the rod with no heat losses along the side of the rod. The theoretical solution of this one-dimensional linear heat flow problem is given by Carslaw and Yeager,[2] Fourier,[3] and Woisard[1] as being

$$T=\theta_0(4\pi Dt)^{-\frac{1}{2}}\exp(-x^2/4Dt), \tag{1}$$

where $D$ is the diffusivity and $T$ is the temperature of the rod at position $x$ at time $t$.

The most convenient form of Eq. (1), for the analysis of data is

$$D=[x^2/2\ln(t_1/t_2)][(1/t_1)-(1/t_2)], \tag{2}$$

where $t_1$ and $t_2$ are successive arrival times of the particular but undetermined temperature at position $x$ on the rod. Data were collected from a curve drawn by a strip-chart recorder of the temperature history of thermocouple positions. The successive arrival times of any particular temperature at a given thermocouple was measured. Time $t=0$ is indicated on the record by a sharp spike caused by an inductive effect of the discharge of the capacitor bank. The temperature at which the arrival times were measured is not needed in the analysis.

The results of tests on "A" nickel, 99.45% pure, obtained from Whitehead Metals, Inc., are presented in Fig. 1 and compared with the data calculated from high-temperature values of thermal conductivity, specific heat, and thermal linear expansion.[4] These data show an inflection point that is also observed in the results of this experiment. Also shown in Fig. 1 are the results of Sidles and Danielson's[5] test on "A" nickel obtained from the Driver Harris Company.

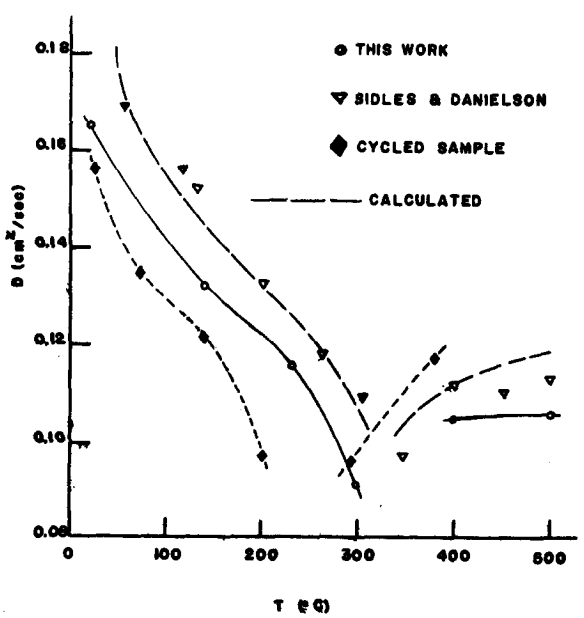


FIG. 1. Temperature variation of thermal diffusivity of nickel.

Sidles and Danielson's extensive work on nickels of various purities show a lowering of diffusivity values as impurities increase. The lower diffusivity values for "A" nickel found in this work are probably due to the difference in compositions of the nickel. Figure 1, in addition, includes results of the determination of thermal diffusivity of nickel by an alternative method that involves temperature values. Accurate measurement of temperatures from most of the records obtained in this experiment was very difficult, so that the results of this determination are unreliable. They are presented here, however, in corroboration with the findings of Butler and Inn[6] that the thermal diffusivity is dependent upon the thermal history of the material. The nickel sample which yielded these results had previously been subjected to four high-temperature cycles in the furnace during early phases of the work when the experimental apparatus was being checked out. This curve also indicates that the Curie temperature is dependent upon the thermal history of the sample. This was reported in NBS circular 485.

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## Electric Field Penetration into Metals

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A TREATMENT based on the degenerate Fermi–Dirac distribution of electric field penetration into metallic electrodes in contact with a dielectric material has recently been presented by Ku and Ullman.[1] They pose the question of why this effect (and the resulting field-independent capacitance contributed by the electrodes) has not been reported or discussed in the past. It is worth pointing out that electric field penetration into metals has, indeed, been considered previously in some detail.

In 1928, Rice[2] used degenerate Fermi statistics to investigate field penetration into metals; his result for a mercury electrode was that the diffuse space-charge layer in the metal in the experimental range of interest acted, as a first approximation, like a constant capacitance arising from plane-parallel (equipotential) electrodes separated by a fraction of an angstrom of vacuum. Ku and Ullman found, within the limitations of their model, the combined capacitance of two identical metallic electrodes with a dielectric slab separating them to be field-independent to higher fields than that of a single metallic electrode abutting an equipotential plane.

The question of determining the "real" or effective surface of a metal has also arisen in adsorption studies where the effective distance between an adsorbed multipole and the imaging plane in the metal must be determined. This distance frequently includes a fraction of an angstrom of penetration into the metal, thus placing

the imaging equipotential plane behind the outer peripheries of the surface atoms.[3,4]

Rice's result, applied to the junction between a metal and an electrolyte, has been criticized on reasonable grounds by Parsons[5] and, more recently, by Mott and Watts-Tobin.[6] The exponential field distance dependence in the metal mentioned by the latter authors seems to be in excellent semiquantitative agreement with the very nearly exponential potential–distance curve calculated numerically by Ku and Ullman. Mott and Watts-Tobin present arguments to justify the conclusion that field penetration adds about 0.5 Å (very nearly equal to typical Ku–Ullman characteristic lengths) to the imaging plane distance, but does not add a constant capacitance associated only with the characteristic field penetration depth in the metal, in contradistinction to the conclusions of Rice and Ku and Ullman.

A number of other papers[7,8] are pertinent to the present problem. In particular, a detailed treatment based on nondegenerate Fermi statistics of the contact between a metal and an extrinsic semiconductor has been given by Fan[9] in 1942, who also finds an exponential decrease in potential in the metal under certain conditions. Exchange and correlation energies of the electrons in the metal were included in the calculation. When the total potential difference across the metal–semiconductor junction is large compared to $kT/e$, Fan finds that an appreciable proportion of it may occur in the metal.

Finally, Ku and Ullman mention that a nonlinear potential relation may arise in problems involving field-independent capacitances and space-charge distributions. Such nonlinear relations and their influence on over-all differential capacitance (the usual quantity measured; it differs in potential-dependent situations from the static capacitance calculated by Ku and Ullman) have been discussed in detail for the situation of an equipotential plane (the effective surface of a metal) abutting a potential-independent capacitance, either natural or artificially produced, adjoining an exhaustion or accumulation space-charge region.[10] Under some charge exhaustion conditions, the over-all differential capacitance of the system can be essentially potential-independent over a wide but limited potential difference range.

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## Visible Radiation from Metal Anodes Preceding Electrical Breakdown*

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IN a recent paper on electrical breakdown, DeGeeter[1] reported observations of emission of blue light from localized spots on a metal anode preceding breakdown; observations of similar spots have been reported elsewhere.[2] DeGeeter suggested the light from these spots was probably associated with the ionization of anode surface materials by electrons from the cathode. The experiments reported here support a different explanation, i.e., transition radiation, for the observed emission of light. Furthermore, the distribution of light emission from the anode coincides with the distribution of the bombarding electron beam. Finally, this emission of light is not directly associated with the voltage breakdown process since it can be observed at gap current and voltage levels well below those required to initiate breakdown.

Transition radiation was described initially by Lilienfeld[3] in 1919, and has been treated theoretically by Frank and Ginsburg,[4] Beck,[5] and others. It occurs when a moving charged particle, such as an electron, traverses a boundary between two media with different optical properties. Its intensity is greatest for vacuum-to-metal boundaries. According to one theoretical interpretation,[5] the emission of radiation is due to a changing dipole field formed by the moving charged particle and its images in the two media.

There have been a number of experimental investigations of transition radiation; the one that seems most pertinent here is a rather complete study by Boersch *et al.*[6] They used a field emission cathode as a source of electrons with which to bombard clean targets of various metals in a high vacuum. The anode current densities at which they reported seeing visible radiation ranged from 0.1 to 10 mA/cm². Some of the distinguishing features of transition radiation observed by Boersch *et al.*, and in agreement with theory, are the following:

(1) The intensity of the radiation is low, but increases with increasing electron energy and current.

(2) The spectrum is continuous, but with a sharp intensity maximum at shorter wavelengths (i.e., in the blue to ultraviolet range).

(3) The radiation is plane polarized.

(4) The radiation intensity has an angular dependence which varies with anode material.

(5) The radiation intensity is independent (for a given current density) of the temperature of the anode, the pressure within the tube (at least for pressures below $10^{-6}$ Torr), and the degree of contamination of the anode surface.

We have observed radiation with these characteristics in a tube designed to study voltage breakdown between clean tungsten electrodes in ultrahigh vacuum conditions and with varying degrees of cesium coverage. The electrodes were a 0.064-cm-diam sphere and a 1.5-cm-diam disk so mounted that the distance between electrodes could be varied, in order to distinguish between effects due to voltage and those due to electric field. Under all conditions investigated (gap spacings between 2.5 and $7.5\times10^{-3}$ cm, voltages up to 25 kV, gross fields up to 3 MV/cm, cesium coverages from 0 to 0.7 monolayers, and ambient cesium pressures up to $10^{-6}$ Torr), a blue spot became visible on the electrode being used as the anode when the anode current density exceeded a critical value of approximately 1 mA/cm². The light from the spot had a continuous spectrum with the greatest intensity in the blue region, was plane polarized, increased in brightness as the current in the tube increased, and was independent of the degree of oxygen contamination of the electrodes. Thus, it is clear that the observed radiation was transition radiation.

Transition radiation does not seem to be a part of the voltage breakdown process. In the tube described above, the gap current was shown to have a field emission origin, and its relationship to gap voltage was reproducible over the range $1\times10^{-10}$ to $1\times10^{-4}$ A, the latter being well above the current ($\sim10^{-6}$ A) where transition radiation first became visible. We have also observed transition radiation in several ultrahigh vacuum tubes in which electrons from clean tungsten field-emission cathodes bombarded clean tungsten or molybdenum anodes, and for which the current–voltage characteristics were stable and reproducible. The observed spot sizes ranged from 0.1 mm to 1 cm in diameter, depending upon tube geometry. In one tube, in which a comb of 30 closely spaced clean tungsten field-emission tips bombarded a clean tungsten anode plate from a distance of 1 cm, a blue spot on the anode became visible when the current reached $10^{-6}$ A, and was still visible at $5\times10^{-3}$ A when the whole anode had turned dull red ($T=1050$°C) due to bombardment heating. A Fowler–Nordheim plot of the current–voltage data over this current range was linear (see Fig. 1), which indicates that the only electron emission process involved was field emission and rules out the presence of significant ion currents (the small deviation in the high-current region of Fig. 1 can be attributed to enhancement of the electron emission resulting from cathode heating).

It is not unlikely that localized incandescent spots, such as have been reported by Little and Whitney,[7] De Geeter[1] and others, may