54,534

A DIAGNOSTIC TECHNIQUE FOR THE INDIRECT DETERMINATION OF THERMIONIC CONVERTER EMITTER TEMPERATURES*

Daniel R. Wilkins
General Electric Company
Nuclear Thermionic Power Operation

ABSTRACT

A diagnostic method for determining thermionic converter emitter temperatures from experimentally measured output current characteristics is described and applied to the analysis of experimental data from both out-of-pile and in-pile converters. The diagnostic technique is based, in part, on previous analyses of the extinguished mode of converter operation, and in part on semi-empirical arguments. Attractive features of the technique are that it has a potentially high degree of accuracy, does not require special design features or instrumentation on experimental converters, and can be rapidly implemented in practice.

1. INTRODUCTION

It is frequently impractical or undesirable to provide for direct measurement of the emitter temperature in experimental thermionic converters, e.g., for life test and in-pile converters, since the provision of instrumentation for emitter temperature measurements in these converters invariably leads to compromises in the converter integrity. Hence, there is a need for techniques which permit the indirect determination of thermionic converter emitter temperatures from easily measured experimental quantities.

Calorimetry measurements have been extensively used to date to determine thermionic converter emitter temperatures. There are a number of uncertainties in the calorimetry techniques, however, which limit the accuracy of calculated emitter temperatures. Therefore, it has been desirable to search for alternate means for determining thermionic converter emitter temperatures.

The following describes diagnostic techniques for determining emitter temperatures from experimentally measured "ignition currents" and "knee currents" in thermionic converters. For electron-rich converter operating conditions, one or both of these quantities may be readily distinguished in experimental output current characteristics. Attractive features of the proposed diagnostic techniques are that they have a high potential degree of accuracy (estimated to be ± 50°K), permit a rapid determination of emitter temperatures from experimental data, and do not require special instrumentation on experimental converters.

---

*Work was performed under United States Atomic Energy Commission Contract AT(04-3)-189, P.A. No. 32.

DISCLAIMER

2. THEORETICAL CONSIDERATIONS

A "typical" output current characteristic for a thermionic converter operating in the "electron-rich" regime shown in Figure 1. This characteristic exhibits lower and upper branches which are referred to as the extinguished and ignited modes of operation, respectively. The ignited mode of thermionic converter operation yields the highest output power densities and efficiencies. The extinguished mode, however, is better understood theoretically and is of greater value in converter diagnostics.

A comprehensive analysis of the extinguished mode of thermionic converter operation, with emphasis on converter diagnostics, has been presented by Wilkins and Gyftopoulos(1). The authors show that, for appropriately selected converter operating conditions, measurements of the extinguished mode output current characteristic can be used to infer values of the electrode work functions, electrode temperatures, and electron and ion mobilities. The techniques which lead to a determination of thermionic converter emitter temperatures for electron-rich operating conditions are summarized below.

For electron-rich operation the extinguished mode output current characteristic exhibits a "forward saturation current density" J_f (Figure 1). A theoretical expression for this current density is given by the relation(1).

$$J_f = J_r^*/(1 + R_e) ;$$

$$J_r^* = e(2\pi m_e)^{1/4}\, h^{-3/2}(kT_E)^{3/4}\, p_g^{\;1/2} \exp\left[-eV_{ig}/2kT_E\right] ; \qquad (1)$$

where J_r^* is the electron random current density in a neutral plasma in thermodynamic equilibrium with the emitter; R_e is proportional to the number of electron-neutral mean free paths across the interelectrode gap; T_E is the emitter temperature; p_g and V_{ig} are the interelectrode gas pressure and ionization potential, respectively; m_e is the electron mass; and k, h, and e are the Boltzmann constant, Planck's constant and electronic charge, respectively. The parameter R_e is given by the relation(1):

$$R_e = (3/4)\left[T_E/(T_E + T_g)\right]\left[p_g/(kT_g)\right] \sigma_{eg} d = a_f p_g d ; \qquad (2)$$

where T_g is the interelectrode gas temperature; d is the interelectrode spacing; σ_{eg} is the electron-neutral cross section; and a_f is an approximately constant parameter which is defined by Equation (2) and may be inferred from experimental data as discussed in Section 3.

The meaning of Equation (1) is that, for electron-rich conditions, the forward saturation current J_f (Figure 1) depends exponentially on emitter temperature and is independent of the electrode work functions and materials. Therefore, in principle, J_f is a valuable diagnostic parameter. In particular, measurements of J_f for known cesium pressure and interelectrode spacing may be used to infer thermionic converter emitter temperatures.

As a result of leakage currents, volume ionization and other complicating factors it is frequently difficult in practice to identify precisely the saturation current density J_f in experimental output current characteristics. Two quantities which can frequently be identified for electron-rich operation, however, are the "ignition current density" J_{ig} and the "knee current density" J_k. These quantities are shown in the output current characteristic in Figure 1. Since both J_{ig} and J_k are approximately equal to J_f, it is reasonable to assume that the ignition current density and knee current density each satisfy an equation similar to Equation (1). Specifically it is assumed that:

$$J_{ig} = J_r^*/(1 + a_{ig}p_g d) \; ; \tag{3}$$

$$J_k = J_r^*/(1 + a_k p_g d) \; ; \tag{4}$$

where the new constants a_{ig} and a_k are not necessarily equal and are to be evaluated from experimental data (see Section 3).

It should be emphasized that while Equation (1) is based on firm theoretical arguments, Equations (3) and (4) must be regarded as semi-empirical. The utility of these equations in converter diagnostics rests solely upon their ability to describe experimental data within tolerable error margins. This ability is demonstrated in Section 3.

An approximate error analysis of Equation (3) or (4) yields the relation:

$$\frac{\Delta T_E}{T_E} \sim \frac{2kT_E}{eV_i}\left(\frac{\Delta J_m}{J_m} + \frac{\Delta a_m}{a_m}\right) \; ; \; m = ig,\ k \tag{5}$$

In other words, errors in the inferred emitter temperature result from errors in the measured current $J_m (m = ig, k)$ and from uncertainties in the corresponding parameter $a_m (m = ig, k)$. It is shown in Section 3 that a pessimistic estimate of the latter yields $\Delta a_m / a_m \simeq 20\%$ $(m = ig, k)$. Hence, if $\Delta J_m / J_m \simeq 5\%$ $(m = ig, k)$, the diagnostic schemes proposed here may be expected to yield thermionic converter emitter temperatures to within about $\pm 50^\circ$K.

Equations (3) and (4) permit the determination of thermionic converter emitter temperatures for electron-rich converter operating conditions. To apply these equations to converter diagnostics, however, values must be established for the constants a_{ig} and a_k. These values are determined in the following section.

3. COMPARISON OF THEORY AND EXPERIMENT

Ignition Currents: Ignition currents for a W-Ni thermionic converter for a broad range of electron-rich operating conditions have been measured by Wilson(2). These data are shown in Figure 2 on a J_r^*/J_{ig} versus $p_g d$ plot as suggested by Equation (3). Although the data are scattered, they nevertheless fall reasonably close to a single straight line and confirm the utility of Equation (3). From the solid line through the data and the two dashed lines which bound the data in Figure 2, the value of a_{ig} in Equation (3) is inferred to be $a_{ig} = 0.28 \pm 0.05$ (mil x torr)$^{-1}$. This value is in reasonable agreement with independent measurements of the electron-neutral cross section for cesium. In addition, the uncertainty in a_{ig} is within the acceptable range for emitter temperature determinations (see Equation 5).

Knee Currents: Experimental knee current data for electron-rich operating conditions are shown in Figure 3 in a form analogous to that for ignition currents (Figure 2). Two sets of data are shown; the solid points represent measurements by Wilson(2) for a W-Mo converter. Both sets of measurements fall reasonably close to a single straight line, and verify the utility of Equation (4). The constant a_k evaluated as previously discussed in connection with a_{ig} is $a_k = 0.39 \pm 0.06$ (mil x torr)$^{-1}$. The uncertainty in a_k is again within the acceptable range for emitter temperature determinations. It should be noted, however, that a_k exceeds a_{ig} by about 30%; so that it is important to distinguish between ignition currents and knee currents in applying the present diagnostic techniques.

4. EMITTER TEMPERATURE DETERMINATIONS

In this section graphs are presented for the determination of emitter temperatures from measured ignition and knee currents in thermionic converters. An interelectrode spacing of 7 mils is considered for illustration. In addition, operating conditions for which the proposed diagnostic techniques are applicable are estimated for a W emitter.
Figure 4 shows the relationship between ignition current density and inverse emitter temperature for an interelectrode spacing of 7 mils and a range of cesium reservoir temperatures. The plot is obtained from Equation (3) by using the value of a_{ig} inferred from experimental data as described in Section 3. The meaning of Figure 4 is that thermionic converter emitter temperatures may be directly inferred from measurements of the ignition current density for known cesium reservoir temperatures.

The curve marked "$\beta = 1$" (β is the ion-richness ratio) in Figure 4 represents the relation between the emitter and cesium reservoir temperatures for which the emission from a W emitter is estimated to be neutral. This curve is determined from the cesiated tungsten work function data of Rasor and Warner(4) and should be regarded as approximate since individual emitters may differ. For measured ignition current densities above the "$\beta = 1$" curve in Figure 4, the emission is ion-rich and the present diagnostic technique is inapplicable.

Figure 5 shows the relation between the knee current density and inverse emitter temperature determined from Equation (4) for an interelectrode spacing of 7 mils and several cesium reservoir temperatures. The results are analogous to those shown in Figure 4 and may be used for emitter temperature determinations in a like manner. Also shown in Figure 5 is the neutral emission ($\beta = 1$) curve for tungsten, above which the emission is ion-rich and Equation (4) is not applicable.

Thus, for electron-rich operating conditions, either ignition or knee current density measurements may be used to infer thermionic converter emitter temperatures. When possible, for single-cell devices, both measurements should be utilized and the results compared. For multi-cell devices multiple ignition current densities corresponding to multiple cell temperatures may be observed. A qualitative understanding of the thermal power distribution is required, however, to associate the inferred temperatures with specific cells.

5. APPLICATION TO IN-PILE CONVERTERS

I-SCIP: A series of output current characteristics have been measured for an instrumented single cell (I-SCIP) converter. Ignition and knee output current densities are estimated from these characteristics and used here to infer the prevailing emitter temperatures. The emitter temperatures determined in this manner are given in Table 1 and compared with corresponding values obtained from the I-SCIP emitter thermocouples.

The I-SCIP emitter temperatures inferred from measured ignition and knee output current densities (Table 1) are generally about 30 to 60°C above the average of the two emitter thermocouple values. Although this small difference is within the expected accuracy of the present techniques and thermocouple measurements, it may be significant and indicate that the thermocouples measure a depressed temperature at the end of the emitter while the converter diagnostic techniques yield an "average" surface temperature.

SCIP-510: Representative output power density versus test-time data for the SCIP-510 converter is shown in Figure 6a. The results indicate that substantial variations in the output power density (about 3 to 8 W/cm^2) occurred during the 3573 hours of operation of this device.

TABLE 1. SUMMARY OF I-SCIP EMITTER TEMPERATURE DATA

Emitter Temperature °C Determined From:			
Thermocouple No. 1	Thermocouple No. 2	Ignition Current	Ignition Current
1495	1550	1527	1547
1495	1550	1575	1587
1495	--	1575	1587
1502	1565	1575	1587
1500	--	1512	1487
1500	--	1552	1552
1500	--	1517	1522
1500	--	1537	1537
1500	--	--	1567

Four to six output current characteristics (at different cesium reservoir temperatures) have been measured at test-times corresponding to each of the 20 data points in Figure 6a. Each of these characteristics is used in this study to obtain an estimate of the prevailing emitter temperatures. The results for each test-time are then averaged to obtain the emitter temperature versus test-time relation shown as the solid line in Figure 6b.

The present results (Figure 6b) indicate that the SCIP-510 emitter temperature varied significantly between 1400 and 1750°C during the 3573 hours of the life test. Within the accuracy of the present diagnostic techniques, these variations correlate completely with those observed in the measured output power density of the device (Figure 6a). No attempt is made here to isolate the source of the emitter temperature variations. It should be recognized, however, that variations of the observed magnitude could result from comparatively small perturbations in the local neutron flux (± 5 to 10%), or from small variations in the radial position of the device (1/16 to 1/8 inch).

Figure 7 shows the data of Figure 6 on a power density versus emitter temperature plot; the latter coordinate being determined from converter diagnostics. The data points in Figure 7 are connected by straight-line segments showing the order in which the measurements were made. Recognizing a ± 50°C uncertainty in the emitter temperatures of Figure 6, the data fall reasonably close to a single curve and exhibit no systematic degradation in the device performance with increasing test time.

Shown for reference in Figure 7 are power density versus emitter temperature curves obtained by TEECO in 1962 for a W-Mo converter(5), and by Wilson(6) for a W-Nb converter. Both of these converters had a 7-mil interelectrode spacing. The higher performance of Wilson's device is attributed in large part to the use of a very clean, heat-treated W emitter. Note that the SCIP-510 data (Figure 7) generally falls between that obtained in 1962 by TEECO and that obtained recently by Wilson. Hence the performance of SCIP-510 compares favorably with related out-of-pile measurements.

6. SUMMARY AND CONCLUSIONS

Diagnostic techniques are presented for determining thermionic converter emitter temperatures to within ± 50°C from experimental output current characteristics. The techniques were derived from theoretical considerations and are verified with out-of-pile results from research converters. Application of these techniques to the analysis of in-pile I-SCIP and SCIP-510 data yields emitter temperatures which are completely consistent with independent measurements (I-SCIP thermocouples), and device performance characteristics (SCIP-510).

REFERENCES

Symposium

1. D. R. Wilkins, E. P. Gyftopoulos, Proc. 26th Ann. Phys. Elec. Conf., M.I.T., Cambridge, Mass., March 1966.

Private communication

2. V. C. Wilson, G.E. Research & Development Center, Schenectady, N. Y., private communication, May 1966.

Private communication

3. R. Howard, Thermo Electron Engineering Corp., Waltham, Mass., private communication, March 1966.

Journal

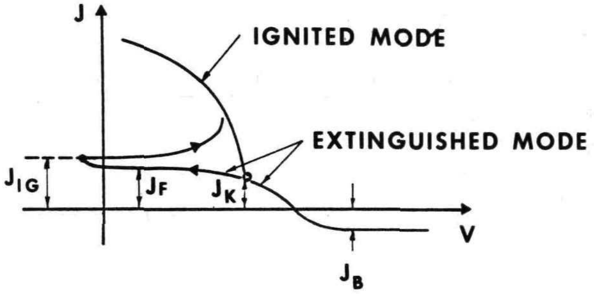
4. N. S. Rasor, C. Warner, J. Appl. Phys., 35, p. 2589, (1964).

Report (non-AEC sponsored)

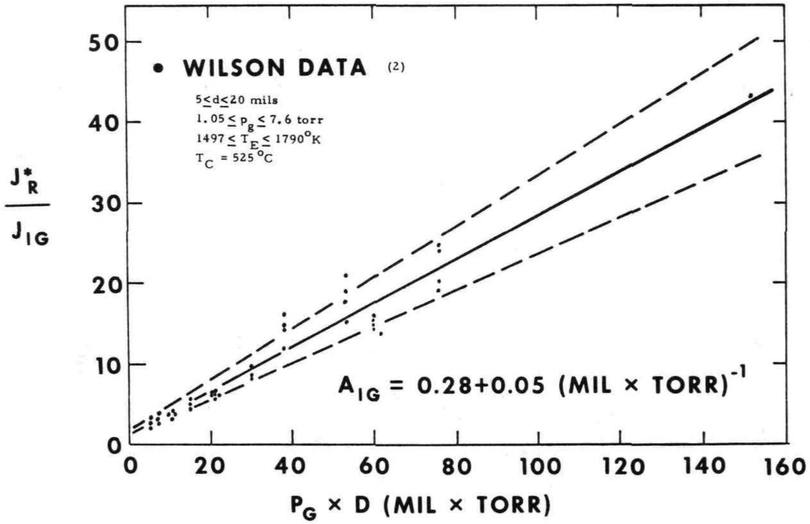
5. S.S. Kitrilakis, M. E. Meeker, N. S. Rasor, "Annual Technical Summary Report for the Thermionic Emitter Materials Research Program," Contract NONR-3563(00), Report No. 2-63, Thermo Electron Engineering Corp., Waltham, Mass., (1962).

Report (non-AEC sponsored)

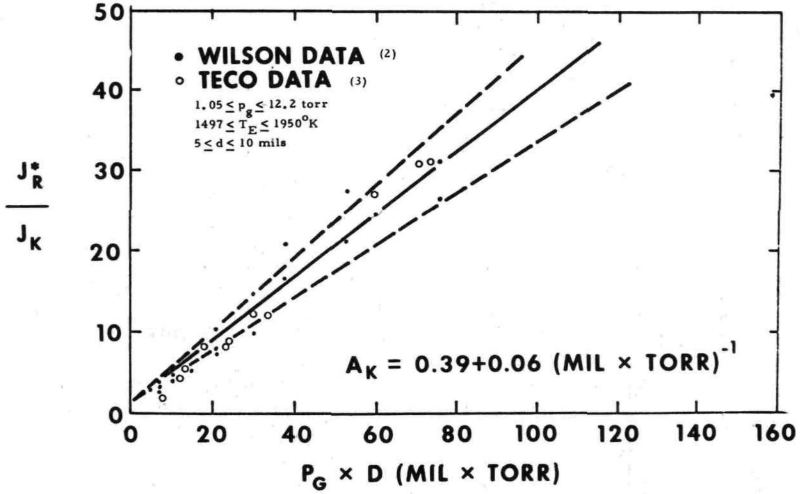
6. V. C. Wilson, J. Lawrence, "A Comparison of Niobium and Nickel as Thermionic Converter Collector Materials," General Electric Co., Report under NASA Contract NAS 3-8511, July 1966.



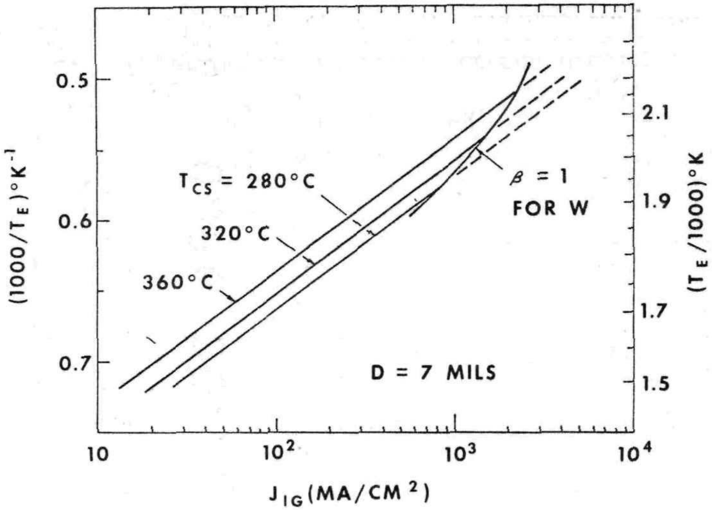
1. Output Current Characteristic (Electron-Rich)



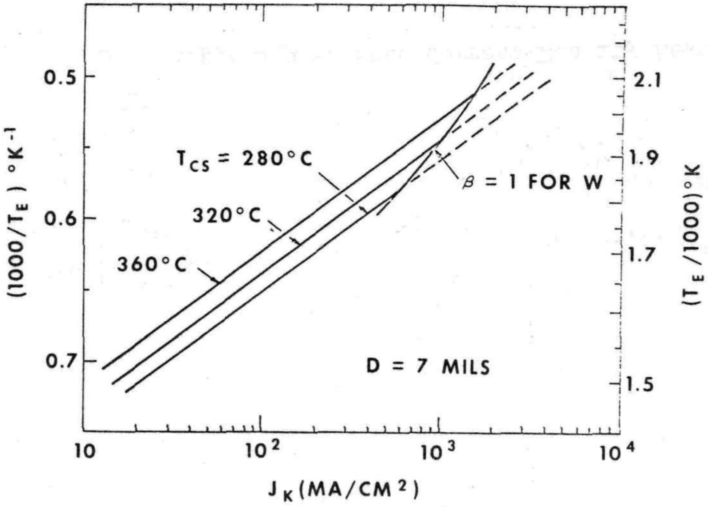
2. Experimental Ignition Current Density



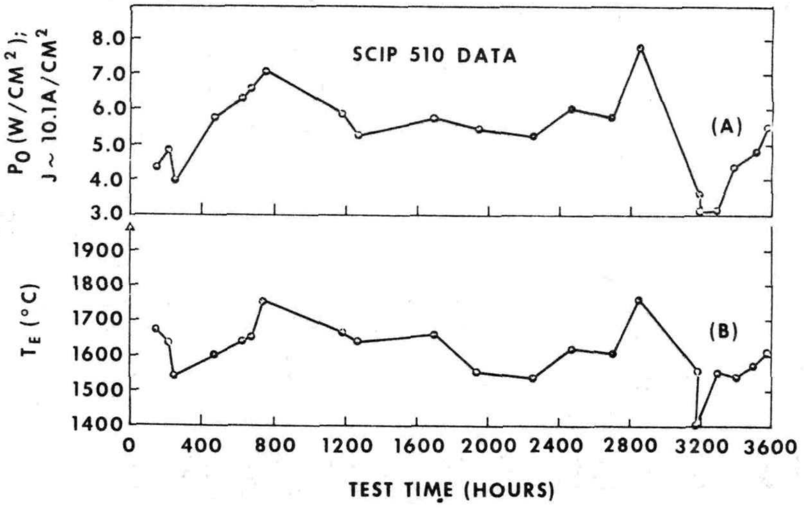
3. Experimental Knee Current Density Results



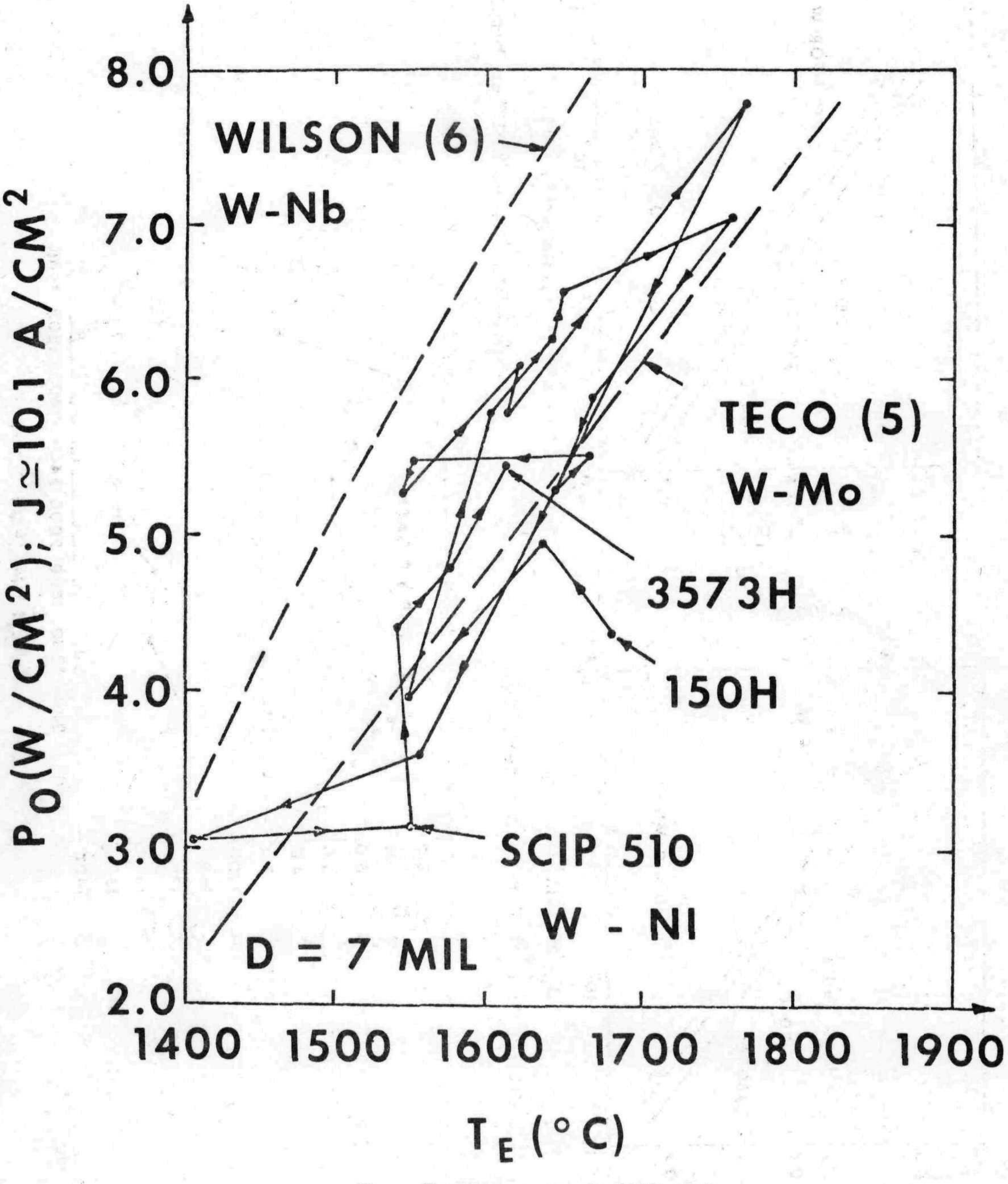
4. Ignition Current Versus Emitter Temp.



5. Knee Current Versus Emitter Temp.



6. Output Power and Emitter Temp SCIP-510



7. Performance of SCIP-510