Scintillator Probes

by

J.C. Sprott

August 1970

PLP 374

Plasma Studies
University of Wisconsin

Scintillator probes are useful for making spatial and time resolved measurements of the electron temperature and density of hot electron plasmas. The technique is not new,[1] but has recently proved especially suitable for use with electron cyclotron heated plasmas in toroidal multipoles.[2,3]

The probes described here consist of a long, 1/4" OD, thin wall, stainless or aluminum tube into which a cylinder (typically 1/8" dia. x 3/8" long) of plastic scintillator (Nuclear Enterprises NE 102) is placed. The circumference of the scintillator is wrapped with lead foil, and one end is covered with a thin (typically .001") layer of aluminum or copper foil that is flush with the end of the 1/4" tube. The other end of the scintillator is bonded to a flexible light guide that carries the light signal to an external photomultiplier tube (6199). A vacuum seal is made with epoxy in the space around the scintillator.

Four scintillator probes have been constructed and are available for use: 1) 24" long with a .001" copper foil. 2) 24" long with a .0007" aluminum foil and a set of additional foils that allow the thickness to be increased in steps of .0007" to .0049". 3) 24" long two-channel probe that has two adjacent scintillators, separated with lead and covered with aluminum foils of .0007" and .0021" respectively. 4) 60" long with a .0007" aluminum foil. Various PM tube circuits are available including a 6 channel version (shown in Fig. 1) constructed in anticipation of a 6 channel probe that has not yet been built.

A scintillator probe is supposedly sensitive only to energetic electrons incident on the foil-covered face. Two processes cause the scintillator to respond: 1) High energy electrons have a range r given by

$$r(\text{microns}) = 0.093\ W^2\ (\text{keV}) \qquad (1)$$

in aluminum foil. Electrons with $W > 43$ keV can penetrate a .0007" aluminum foil and decay in the scintillator. 2) At lower energies (1 - 10 keV), incident electrons can produce x-rays in the foil, and the x-rays easily pass through the foil and deposit their energy in the scintillator. The foil should be sufficiently thick to eliminate background light.

In its crudest form, the scintillator probe provides a qualitative measure of electron energy, since the output signal is a monatonically increasing function of incident electron energy. The scintillator probe is capable of quantitative measurements if properly calibrated. The probe is calibrated with an electron beam of known energy and current. The current can be measured with an electrometer from the probe body to ground, provided the beam is sufficiently focused that it falls only on the foil and provided secondary electron emission is eliminated or taken into account. An efficiency $\eta(W)$ is defined as the ratio of output current from the PM tube to the electron beam current, and takes into account absorption in the foil, efficiency of the scintillator and light guide, and the gain of the PM tube. A plot of $\eta(W)$ for the two channel probe is shown in Fig. 2. At high energies, $\eta(W)$ appears to saturate, but above ~ 43 keV (not shown) $\eta(W)$ for the .0007" foil increases sharply as electrons start to penetrate the foil. The following discussion will assume electron energies sufficiently low that this effect can be neglected.

In a plasma, the electrons are not monoenergetic but have a distribution of energies, f(W). The distribution $\frac{1}{kT} e^{-W/kT}$ is plotted in Fig. 3 along with the functions $f(W)\eta(W)$ for the two cases of Fig. 2. Note that for kT = 1 keV, the channel with the .0007" foil samples predominately particles with W ~ 5 keV while the channel with .0021" foil samples particles with W ~ 9 keV. It is clear that for distributions with low average energies, the scintillator probe responds only to the tail of the distribution, and so the measurement is quite sensitive to variations in the form of f(W).

The output signal from the scintillator probe is given by

$$I = \frac{1}{4} neA\sqrt{\frac{2}{m}} \int_0^\infty W^{1/2} f(W)\eta(W)\, dW \tag{2}$$

where n is the electron density and A is the probe area. f(W) is normalized such that

$$\int_0^\infty f(W)\, dW = 1.$$

The average energy of the distribution can be determined by measuring the ratio of the currents from the two channels with different foil thicknesses. Three different distributions have been considered:

1) $f(W) = \delta(\overline{W})$

2) $$f(W) = \frac{2}{\sqrt{\pi}} \frac{\sqrt{W}}{(kT)^{3/2}} e^{-W/kT}$$

3) $$f(W) = \frac{3}{\overline{W}} e^{-\sqrt{6W/\overline{W}}}.$$

The first is a delta function, chosen for its simplicity. The second is a Maxwellian, and the third is the distribution function measured by Kuswa in the octupole during microwave heating. The calculated ratios are shown in Fig. 4. Note how sensitive the measured energy is to the form of the distribution. Typical experimentally observed ratios are ~ 10 in the small octupole, giving average energies of a few hundred eV, in agreement with electrostatic energy analyzer measurements.[4]

Having determined the average energy by this ratio method, the density can in principle be calculated from the output current using Eq. (2). Figure 5 shows the result of such a calculation for three different distribution functions for the .0007" aluminum foil. The calibration is over a year old and some changes have been made, so the absolute value of the current can no longer be trusted. In any case this method is not very reliable for determining density. Usually the density is known from other measurements. At low gas pressures where ionization is negligible, the density during microwave heating is assumed to be the same as just before the heating pulse. If the density is known (even approximately), the average energy can be estimated from Fig. 5 if the form of f(W) is known. In any case, note that the scintillator probe signal is roughly proportional to $\overline{W}^{3.5-4}$ for all three distributions. The signals observed with the levitated octupole are several orders of magnitude larger than for the small octupole for the same density, from which we conclude that typical average electron energies during microwave heating are ~ 1 - 10 keV, in agreement with theoretical predictions.[5]

Several precautions are necessary in using scintillator probes. The effect of energetic electrons that penetrate the foil has already been mentioned. It is also possible that x-rays produced by the plasma or on the vacuum tank walls could give a background reading on the probe that confuses spatial measurements. In addition, the calibration was made with an electron beam incident normally on the probe surface. The calculations for a plasma assumed an isotropic velocity distribution and an efficiency $\eta(W)$ that depends only on incident energy and not on the angle of incidence. The validity of this assumption has not been tested.

Pin holes in the foil can produce erroneous signals caused by light from the plasma or elsewhere. Light leaks can be identified by exposing the probe to a 60 cycle incandescent lamp and looking for a 60 cycle component on the PM tube output. A leak can be localized by using a black paper with a pin hole to illuminate only a small area and can be repaired with a dab of epoxy mixed with graphite. In a plasma, the probe can be tested by raising the background gas pressure. In every case observed so far, the light signal increases and the electron energy desreases with increasing pressure.

The photomultiplier tube should be kept away from magnetic fields and the gain of the tube kept sufficiently low that saturation does not occur. The time constant of the PM tube load should be long compared with the average duration between light pulses but short compared with the time over which the electron energy changes appreciably.

If the form of the distribution is not known, it could perhaps be determined by measurements with a multi-channel probe. The mathematical problem is rather difficult and would probably require a computer. It may also turn out that even with an arbitrarily large number of measurements, there is an ambiguity in f(W) that cannot be resolved by this technique without additional assumptions or measurements.

ACKNOWLEDGMENTS

The difficult job of constructing the scintillator probes was performed by Paul Nonn. Glenn Kuswa assisted in calibrating the probes with an electron beam.

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4. J.C. Sprott and G. Kuswa, Bull. Am. Phys. Soc. II, 14, 726 (1969).
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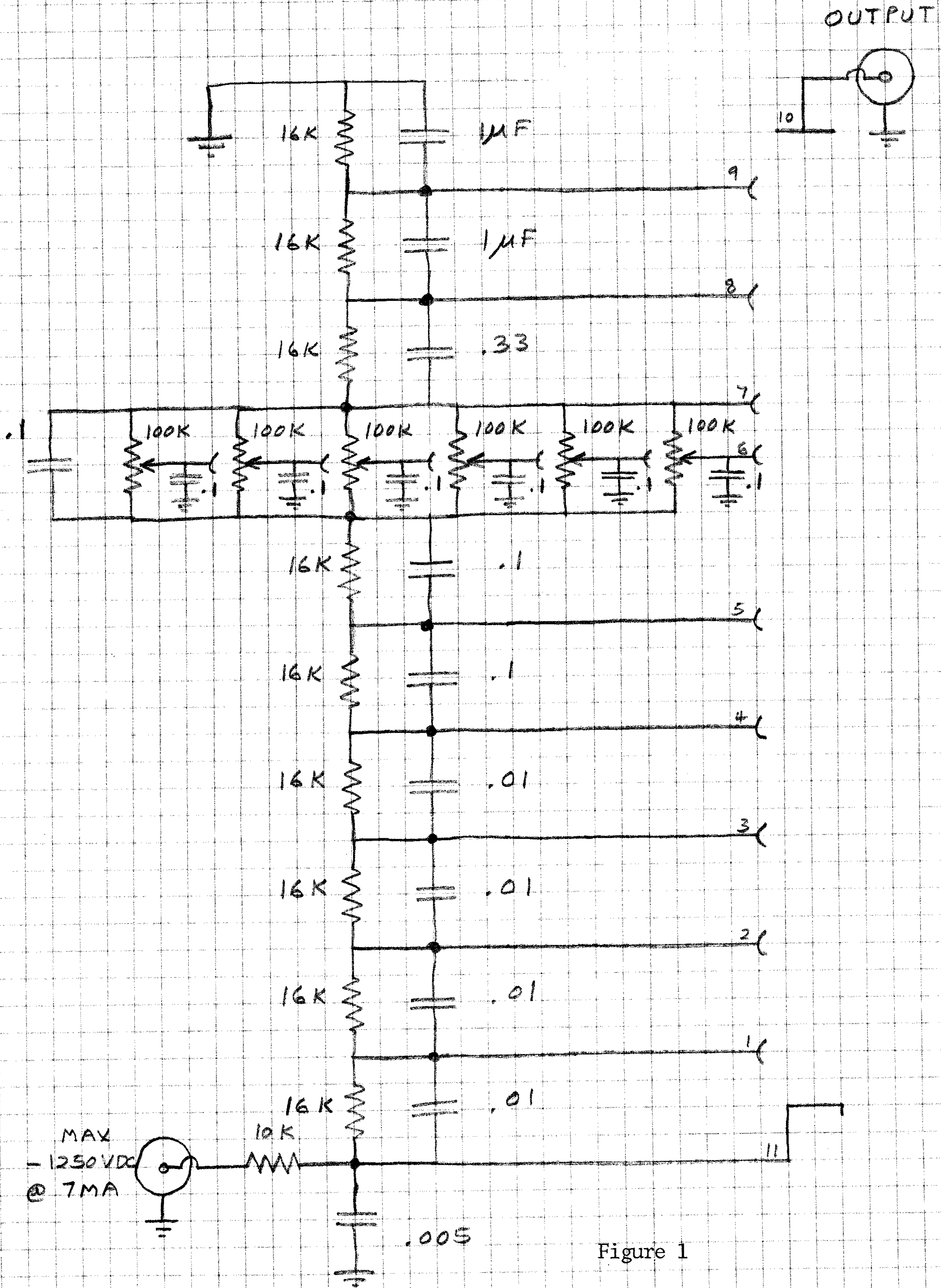


Figure 1

SIX CHANNEL PM TUBE CKT

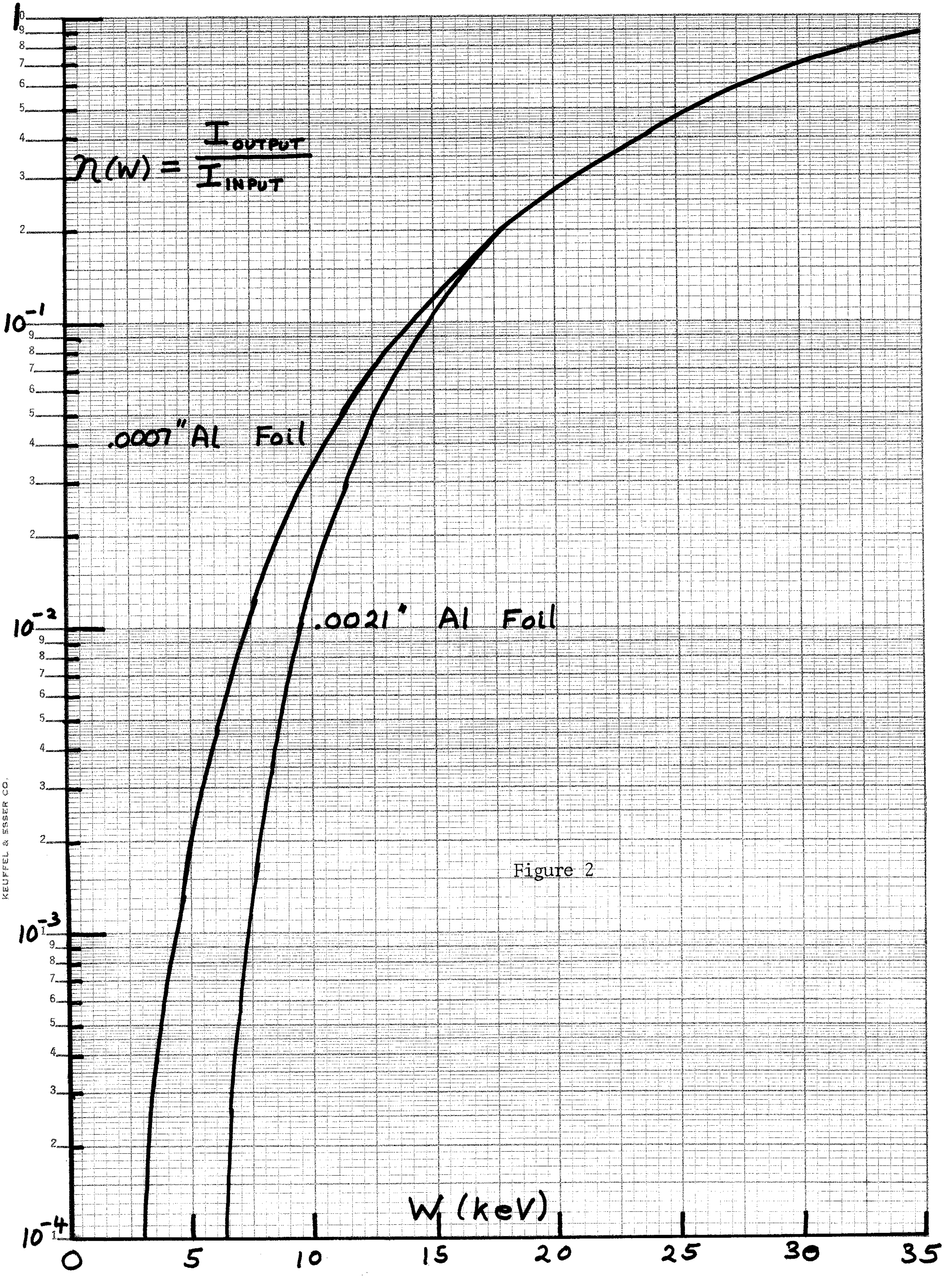

1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\eta(W) = \frac{I_{OUTPUT}}{I_{INPUT}}$
.0007" Al Foil
.0021" Al Foil
W (keV)
0
5
10
15
20
25
30
35

Figure 2

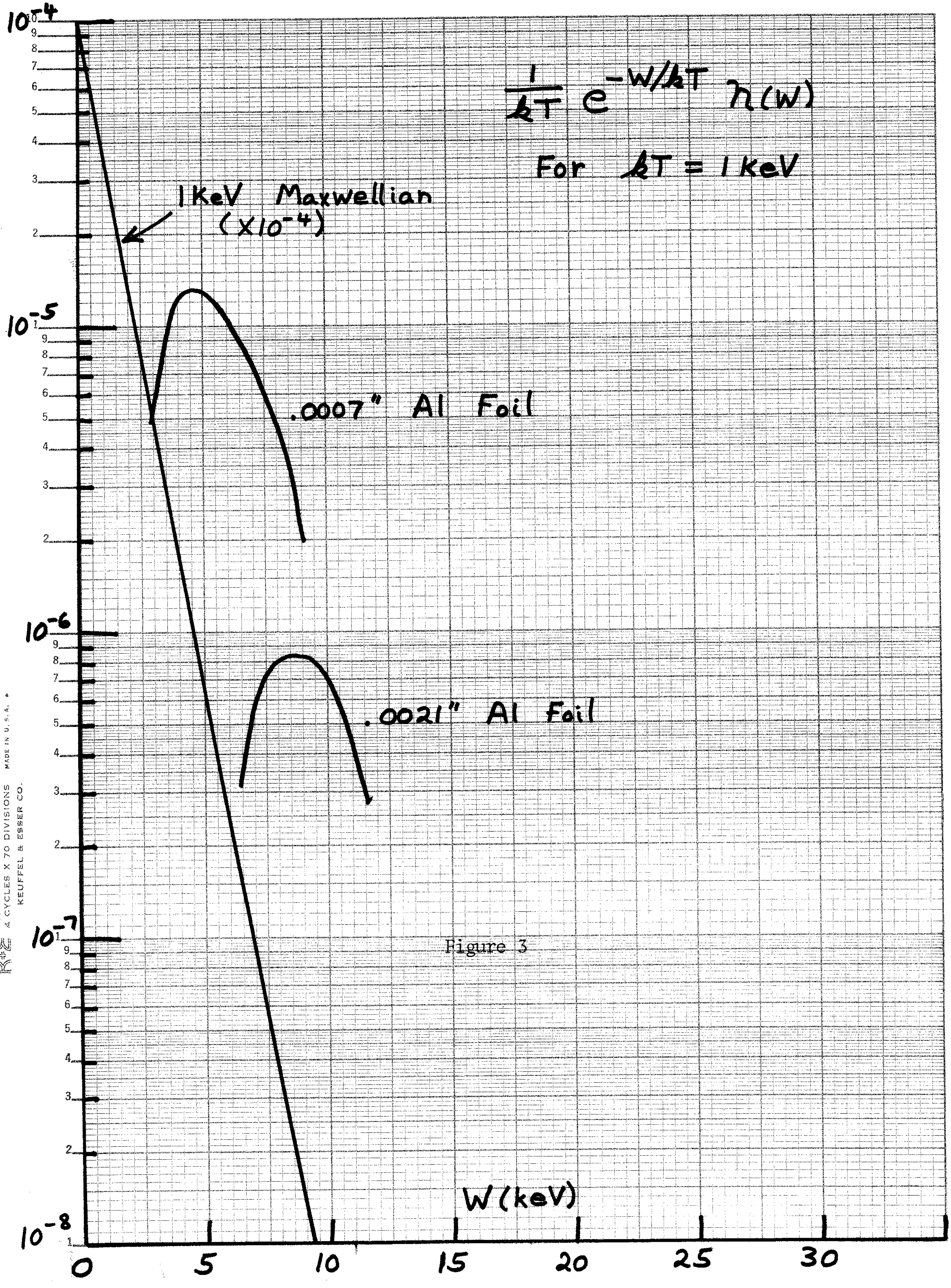
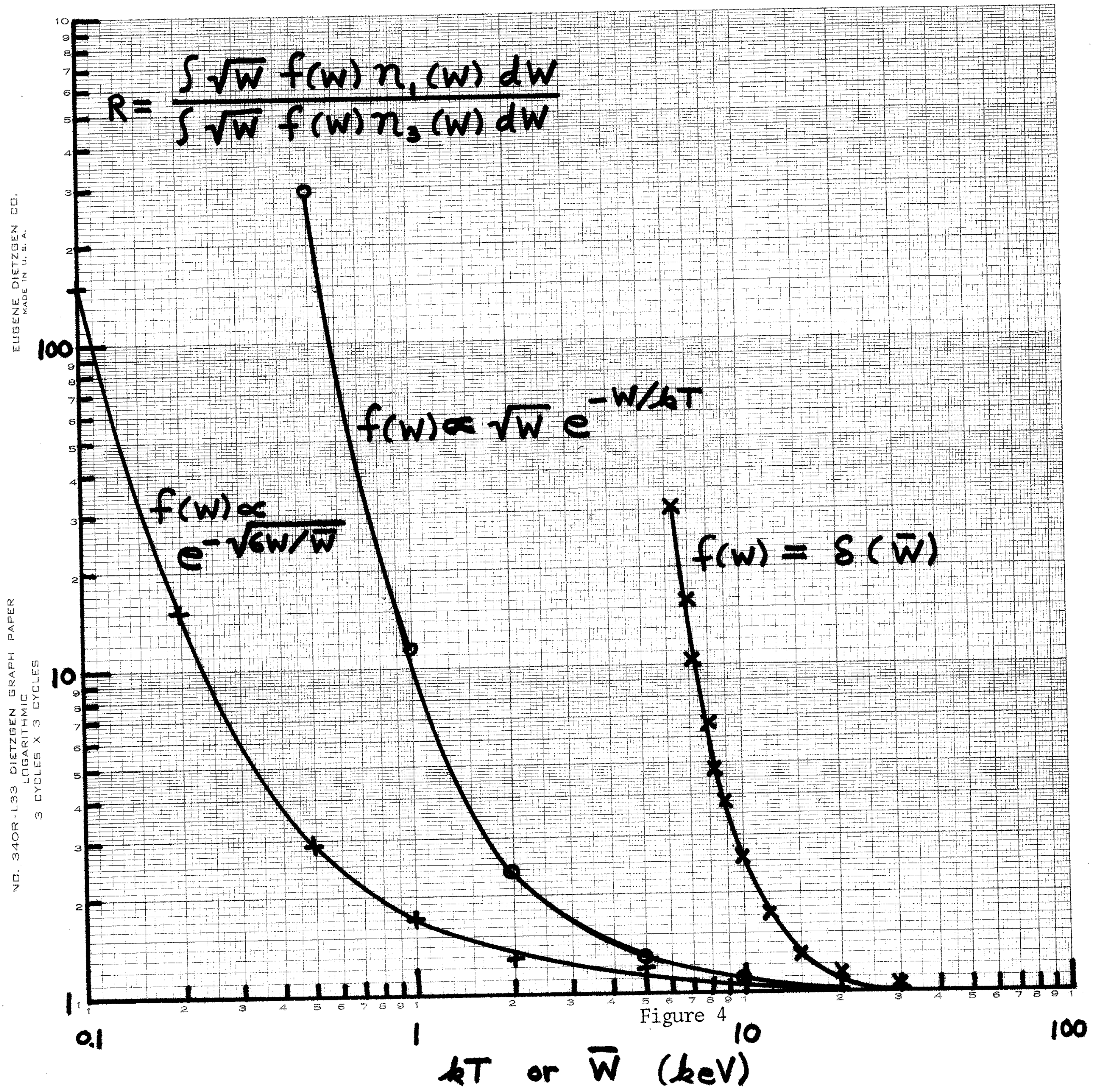
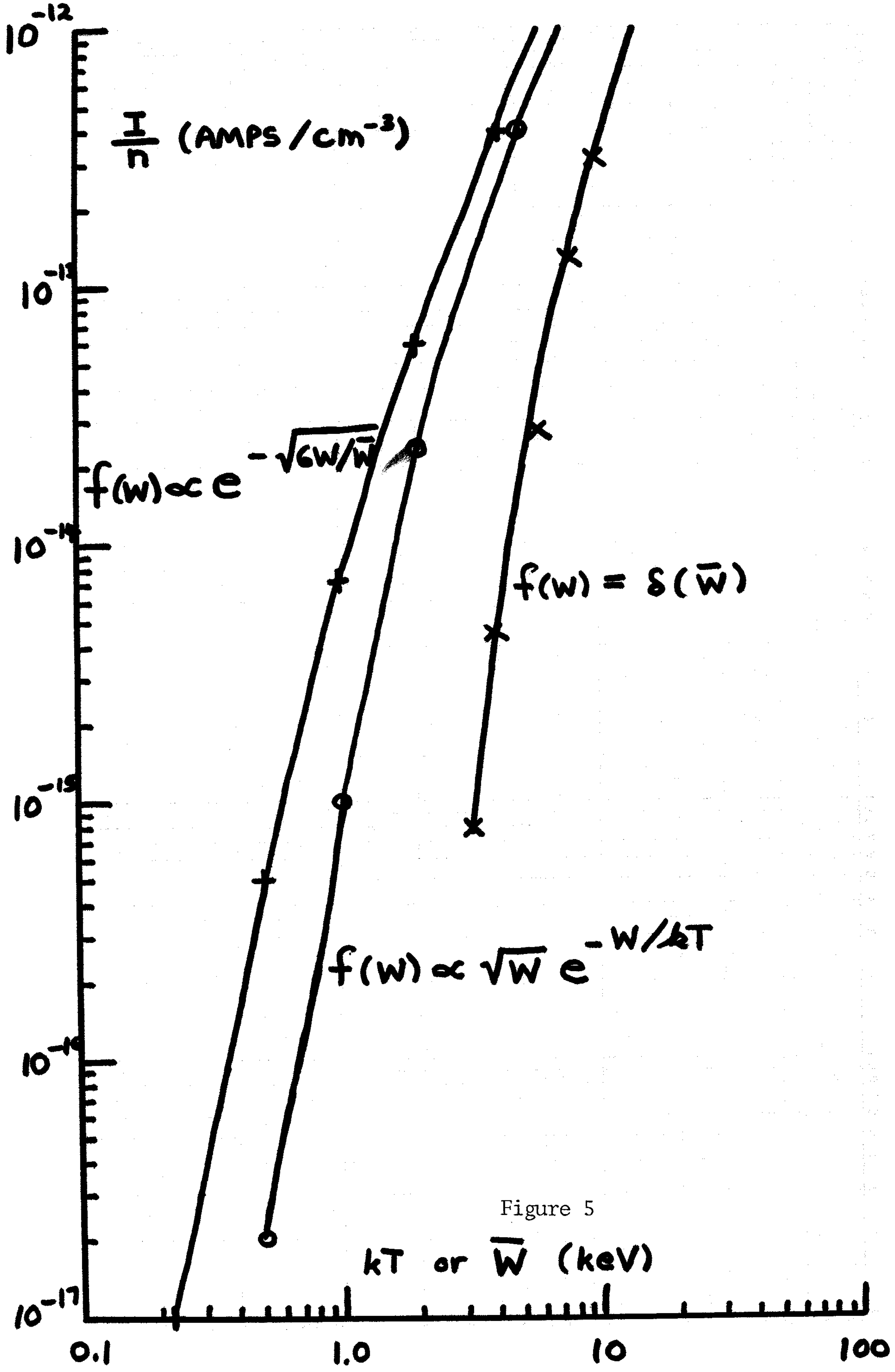

$\frac{1}{kT} e^{-W/kT} \eta(W)$
For kT = 1 keV
1 KeV Maxwellian (X10^{-4})
.0007" Al Foil
.0021" Al Foil
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
W (keV)
0
5
10
15
20
25
30

Figure 3



$R = \frac{\int \sqrt{W}\, f(W)\, n_1(W)\, dW}{\int \sqrt{W}\, f(W)\, n_3(W)\, dW}$
$f(W) \propto \sqrt{W}\, e^{-W/kT}$
$f(W) \propto e^{-\sqrt{6W/\bar{W}}}$
$f(W) = \delta(\bar{W})$
100
10
1
0.1
1
10
100
kT or $\bar{W}$ (keV)
EUGENE DIETZGEN CO.
MADE IN U. S. A.
NO. 340R-L33 DIETZGEN GRAPH PAPER
LOGARITHMIC
3 CYCLES X 3 CYCLES

Figure 4



10^{-12}
$\frac{I}{n}$ (AMPS / cm^{-3})
10^{-13}
$f(W) \propto e^{-\sqrt{6W/\overline{W}}}$
10^{-14}
$f(W) = \delta(\overline{W})$
10^{-15}
$f(W) \propto \sqrt{W}\, e^{-W/kT}$
10^{-16}
kT or $\overline{W}$ (keV)
10^{-17}
0.1
1.0
10
100

Figure 5