

## A NEW ABSOLUTE NOISE THERMOMETER AT LOW TEMPERATURES<sup>1</sup>

H. J. FINK<sup>2</sup>

### ABSTRACT

If three resistors, which are kept at different temperatures, are arranged in form of a  $\pi$  network and if two of the thermal noise voltages appearing across the  $\pi$  network are multiplied together and averaged with respect to time, then under certain conditions the correlation between those voltages can be made zero. This condition is used to calculate the temperature of one noise source provided all the resistance values and the other temperatures are known. A noise thermometer of this kind was constructed which is capable of measuring temperatures below approximately 140° K. The boiling points of liquid oxygen and liquid nitrogen were determined absolutely within 0.2%. Between 1.3° K and 4.2° K the thermometer had to be calibrated due to errors arising in the equipment and the measured temperatures were then accurate within  $\pm 1\%$ .

### 1. INTRODUCTION

This paper deals with the construction of a thermometer which makes use of the thermal fluctuations of voltage across an impedance to measure absolutely temperatures below approximately 140° K. Preliminary investigations were carried out for such a device to measure accurately temperatures in the liquid helium region.

According to Nyquist's (1928) law the mean-square voltage fluctuations arising from the thermal agitation of the electrons across an impedance,  $Z$ , are given by:

$$(1) \quad \overline{v^2} = 4kT \operatorname{Re}[Z] p(f, T) df,$$

where  $k$  is Boltzmann's constant,  $T$  the absolute temperature,  $\operatorname{Re}[Z]$  is the real part of the complex impedance,  $Z$ ,  $p(f, T)$  the Planck factor, and  $df$  the frequency interval in which the measurements are performed. The above formula can be derived from the equipartition law and the second law of thermodynamics and the available noise power is a universal function of the frequency and the absolute temperature (see also Van der Ziel 1954). Equation (1) has also been proved for models which describe the random motion of the electrons in a conductor (Bernamont 1937; Bakker and Heller 1939; Spenke 1939). Nyquist's theorem can also be proved for the one-dimensional form of black-body radiation (Burgess 1941) which is received by an antenna kept in a sphere at uniform temperature. The thermodynamic method has the merit that it is independent of the mechanism causing the noise.

A number of papers have been published (Lawson and Long 1946; Brown and MacDonald 1946; Gerjuoy and Forrester 1947; Cook, Greenspan, and Wussler 1948) which suggests the possibility of using thermal fluctuations of

<sup>1</sup>Manuscript received July 15, 1959.

Contribution from the Department of Physics, University of British Columbia, Vancouver, British Columbia.

<sup>2</sup>Present address: The Clarendon Laboratory, Oxford, England.

voltage across an impedance to measure low temperatures but they do not propose any practical scheme for a thermometer of this kind and no serious attempt has been reported which indicates that such an experiment has been performed at low temperature.

In 1946 Dicke *et al.* reported a radiometer which measures thermal radiation at microwave frequencies. This method is essentially a commutation comparison technique which compares the unknown noise with that of a standard source. The radiometer has been used for observations of microwave radiation from the sun and the moon and for the measurement of atmospheric absorption at several microwave frequencies. Garrison and Lawson (1949) developed an absolute noise thermometer of the Dicke type to measure high temperatures. A chopper at the input of the amplifier is used to connect alternately the thermometer resistor and a resistor at ambient temperature (standard noise source). The principal limitation of such a switching device for comparison of noise voltages is the variation in contact potential of the chopper. Also the ultimate sensitivity of such a thermometer depends upon the noise-signal-to-amplifier-noise ratio. Aumont and Romand (1954) attempted an improvement of Garrison's and Lawson's thermometer, but the final results have not yet been reported. The National Physical Laboratory (1957) reports also an improved noise thermometer for high temperatures ( $\sim 1100^\circ \text{C}$ ) based on the switching technique which is capable of comparing noise voltages to 0.05%. Cade (1958) uses an electronic switch instead of a chopper.

To avoid any switching device at the inputs of the amplifier and to make noise measurements virtually independent of the amplifier noise, one can arrange three resistors, which are kept at different temperatures, in form of a  $\pi$  network; and if now two of the thermal noise voltages appearing across the network are multiplied together and averaged with respect to time, then under certain conditions the correlation between those voltages can be made zero. From this condition one can calculate the temperature of one noise source,

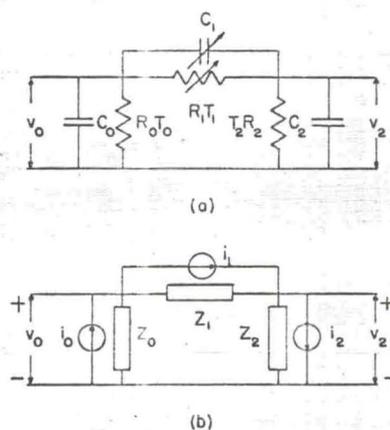


FIG. 1. (a) The  $\pi$  network as used to correlate noise between  $R_0$  and  $R_2$  via  $R_1$ .  
 (b) The block diagram and the equivalent noise current sources of the  $\pi$  network.

provided all the resistance values and other temperatures are known.<sup>3</sup> Consider the network of Fig. 1. By straightforward network analysis one obtains for  $v_0$  and  $v_2$ :

$$(2a) \quad v_0 = \frac{Z_0}{Z_T} [i_0(Z_1 + Z_2) - i_1 Z_1 - i_2 Z_2]$$

$$(2b) \quad v_2 = \frac{Z_2}{Z_T} [i_0 Z_0 + i_1 Z_1 - i_2(Z_1 + Z_0)]$$

where

$$Z_T = Z_0 + Z_1 + Z_2, \quad Z_0 = R_0 / (1 + j\omega C_0 R_0), \text{ etc.}$$

and  $v_0$ ,  $i_0$ , etc. are complex vectors. If one multiplies  $v_0$  and  $v_2$  and takes the time average over the product, then one forms:

$$(3) \quad \text{Re}(\overline{v_0 v_2^*}) = \text{Re} \left\{ \frac{Z_0 Z_2^*}{|Z_T|^2} [ |i_0|^2 Z_0^* (Z_1 + Z_2) + |i_2|^2 Z_2 (Z_0^* + Z_1^*) - |i_1|^2 |Z_1|^2 ] \right\},$$

where

$$|i_0|^2 = 4kT_0 df / R_0$$

(the Planck factor is assumed to be unity), similarly  $|i_1|^2$  and  $|i_2|^2$ . The time average of the products  $\text{Re}(i_0 i_1^*)$ , etc. are zero because the resistors are independent noise sources. The product  $\text{Re}(\overline{v_0 v_2^*})$  appearing in equation (3) corresponds to the direct multiplication of the physical voltages  $v_0$  and  $v_2$ . From equation (3) one sees that if either  $R_0 C_0 = R_1 C_1 = R_2 C_2$  or  $(\omega R_n C_n)^2 \ll 1$  the product  $\text{Re}(\overline{v_0 v_2^*})$  can have a positive or a negative sign provided  $T_1 > (T_0 + T_2)$ . For either of the above conditions the value of  $R_1$  required to make  $\text{Re}(\overline{v_0 v_2^*}) = 0$  can be calculated from equation (3):

$$(4) \quad R_1 = \frac{T_0 R_2 + T_2 R_0}{T_1 - T_0 - T_2}$$

In this experiment  $R_0$  and  $R_2$  were both kept in the helium bath so that  $T_0 = T_2$ .  $R_2$  and  $R_0$  were matched to better than 1/2%, and  $T_1$  was in an isothermal bath at room temperature. If  $T_1$  and the resistances are measured,  $T_0$  can be calculated from

$$(5) \quad T_0 = T_1 \frac{R_1}{R_0 + 2R_1 + R_2}$$

## II. THE THERMOMETER AND EXPERIMENTAL PROCEDURES

The first requirement for an absolute noise thermometer of the kind described above is to find some resistors which are stable at liquid helium temperatures, whose values are preferably reproducible for several experiments, which produce no noise in addition to thermal noise, and whose resistive component

<sup>3</sup>This idea was proposed by Dr. J. B. Garrison to Prof. A. W. Lawson of Chicago University (verbal communication by Prof. R. E. Burgess).

is the same as the d-c. resistance (within a specified accuracy) over the frequency interval in which the measurements are performed. Many resistors have been tried at helium temperatures. The ones found most suitable are those manufactured by the Daven Co., series 850. They are hermetically sealed precision metal film type resistors composed of an alloy of pure, noble metals. They are stable over a period of at least 7 hours to better than 1 part in  $10^4$  and they are reproducible to that accuracy for several experiments. A 20-k $\Omega$  resistor has a resistive component of  $20\text{k}\Omega \pm 1\%$  at 3 Mc/sec. The resistance values used in equation (5) should be those appropriate to the frequency range in which the noise measurements are performed. Because no sufficiently accurate audio-frequency bridge was available the metal film deposit resistors were measured at d-c. and at 3 Mc/sec. Since the 3-Mc/sec values differed from the d-c. values by less than 1%, it seems reasonable to conclude that the deviation of the resistance in the audio-frequency range from the d-c. value was less than 0.1% for the above resistors. A 20-k $\Omega$  Davohm resistor has a resistance of approximately 17.9 k $\Omega$  at liquid helium temperatures (1.3° K to 4.3° K) and the resistance value over this range varies less than 0.05%.

$R_1$  was a precision wire wound resistance box and  $C_1$  a variable condenser, both kept at room temperature.  $C_0$  and  $C_2$  were the parasitic capacitance between the wires and the shielding, and the input to the amplifiers (including effects due to Miller capacitances), and they were equal within 3%. Unfortunately the parasitic capacity to ground was very large ( $\sim 220 \mu\text{mf}$ ), and about three-fifths of this was due to the shielding of  $C_1$  and  $R_1$  which was reflected into the input of each amplifier.

Figure 2 shows the block diagram of the thermometer. The shielding requirements of the input circuit and the preamplifiers were very stringent and great care was required to avoid ground loops and to eliminate magnetic pickup in

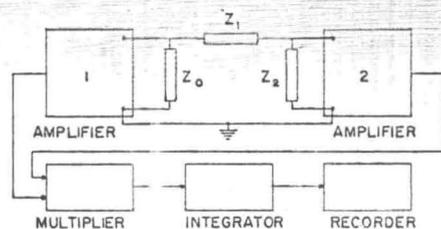


FIG. 2. The block diagram of the noise thermometer.

the  $\pi$  network which in effect act like a loop. The first tube of the preamplifier was a 6922 (American equivalent to the Philips E88CC) double triode connected as a grounded-cathode-grounded-grid amplifier (cascode) followed by two RC coupled stages (7025 double triode). The cascode and the first RC coupled stage were constructed of wire wound resistors, and their filament currents were supplied by batteries. The lower and upper half power points of the amplifiers were approximately 3 and 7 kc/sec respectively. Both input voltages to the multiplier were constantly monitored by two oscilloscopes and two r.m.s. voltmeters to check the randomness of the noise spectrum and

the gain of the amplifiers. The multiplier (a commercial type manufactured by G. A. Philbrick, Inc.) is followed by an amplifier and an RC integrator of variable integration time (22.5 to 90 seconds). The output of the integrator was fed into a recorder via a cathode follower to permit better registration of the time average of the signal.

$R_0$  and  $R_2$  were carefully cooled to liquid helium temperatures and then their d-c. value was measured with a Wheatstone bridge ( $R_1$  and  $C_1$  were disconnected).  $R_1$  was set to approximately the value at which balance [ $\text{Re}(v_0 v_2^*) = 0$ ] was expected and  $C_1$  adjusted such that  $R_1 C_1 \simeq R_2 C_2$ . This was accomplished by connecting  $Z_1$  and  $Z_2$  in series and applying pulses across  $Z_1$  and  $Z_2$ .  $C_1$  was then adjusted until the shape of the pulses across the impedance  $Z_1 + Z_2$  and  $Z_2$  were identical. This procedure adjusted the time constants  $\tau_1$  and  $\tau_2$  to approximately 10%. Similarly  $\tau_0$  and  $\tau_1$  were adjusted and the average setting of  $C_1$  was used when  $R_1$  was varied to achieve balance. If the change in  $R_1$  was large  $\tau_1$  had to be rebalanced and  $R_1$  reset. The temperature (room temperature) of  $R_1$  was read on an ordinary mercury thermometer placed on the outside of the resistance box and the value of  $R_1$  was read from the dial setting of the resistance box. The temperature of the helium bath was then calculated from equation (5).

The temperature of the helium bath was sometimes kept constant to better than 1 millidegree K by a temperature regulator (400 c.p.s.) similar to that of Boyle and Brown (1954). A stirrer was sometimes used to equalize the temperature, and the vapor pressure of the helium was measured on a mercury manometer with a cathetometer. A German silver tube (8-mm diameter) extending into the liquid surface was connected to the manometer. The temperature determined from equation (5) was then compared with the "1958 <sup>4</sup>He scale of temperatures" (Van Dijk and Durieux 1958; Brickwedde 1958).

### III. ERRORS AND LIMITATIONS OF THE THERMOMETER

#### 1. Errors Which Can Be Represented by Noise-Current Sources in Shunt with the $\pi$ Network

These errors can be divided essentially into two groups: (a) errors due to the grid currents, (b) errors due to the finite input admittance.

(a) The grid current is made up of three parts; electrons arriving at the grid ( $I_1$ ), electrons emitted from the grid by photoelectric emissions ( $I_2$ ), and positive ions arriving at the grid ( $I_3$ ). All three currents are independent of each other. The grid of the triode acts like the anode of a diode; for  $I_1$  it acts like the anode in the exponential part of its characteristic and for  $I_2$  and  $I_3$  it acts like the anode of a saturated diode. Therefore the shot noise due to the grid current is:

$$(6) \quad \overline{i_g^2} = 2e(I_1 + I_2 + I_3) df.$$

The net grid current is  $I_g = I_1 - I_2 - I_3$  and thus  $i_g^2 \geq 2eI_g df$ .

(b) The real part of the dynamic input admittance which is a function of frequency consists of three components: the ohmic loss in the input circuit, the cold loss of the first stage (leakage around the bulb of the tube, losses in

the socket, etc.), and part of the load of the first stage which is reflected into the input due to the grid-to-plate capacity. In this experiment a cascode input was used which has the advantage that the grounded grid stage reduces the capacitive feedback from output to input without introducing partition noise. However, due to the finite feedback shot noise of the grounded grid stage contributes also to this error.

The errors in (a) and (b) can be represented by noise-current sources in shunt with the  $\pi$  network. The noise temperature which must be ascribed to this input conductance cannot be determined by calculation because its components and their noisiness are not readily estimated. If one assumes that the real part of the input impedance to the amplifiers is  $R_g$  and its effective temperature is  $T_g = \alpha T_0$ , where  $\alpha$  is a constant and  $T_0$  is room temperature, and if one also assumes that both amplifiers have the same input characteristics and that  $R_g \gg R_0$  and  $R_0 \simeq R_2$ , then the error in the absolute temperature due to shunt current sources is:

$$(7) \quad \epsilon = \frac{\Delta T}{T} \simeq \frac{R_0}{2kT} \left[ e(I_1 + I_2 + I_3) + 2k \frac{\alpha T_1}{R_g} \right] = \frac{A}{T},$$

where  $A$  is a constant for one particular thermometer.

### 2. Errors Due to Current Flow in the Resistors

Nyquist's law is based upon the assumption that the circuit is a passive network. This requires that no currents are flowing through the resistors  $R_0$ ,  $R_1$ , and  $R_2$ . To minimize thermoelectric effects dissimilar materials between the amplifiers and resistors in the network were avoided and the voltage due to this effect was measured to be smaller than  $3 \mu\text{V}$  at the inputs of the amplifiers when  $R_0$  and  $R_2$  were at helium temperatures. The grid current  $I_1 - (I_2 + I_3)$  was approximately  $2.6 \times 10^{-9}$  amperes. Because thin metal layer resistors ( $R_0$  and  $R_2$ ) consist of a large number of very small conducting particles in loose contact, contact noise may be generated if a current is passed through the resistors. Christenson and Pearson (1936) did not find any contact noise in thin solid carbon filaments when large currents were passed through the specimen. Also Bittel and Scheidhauer (1956) found no noise in addition to the thermal noise when a current was passed through metallic conductors between 45 c.p.s. and 11.5 kc/s. Therefore thin solid metal layer resistors should be free of any noise in excess of thermal noise and Nyquist's law should hold accurately for the above small currents.

### 3. Non-linearities and Amplifier Noise

Non-linearities in the amplifiers, the multiplier, and the integrator are another source of error. Due to non-linearities the recorder deflection will be increased by an increment proportional to  $(|v_0^2| |v_2^2|)^{1/2}$ . Because for  $Z_1 = \infty$  as well as for balance (see equation 5) the correlation coefficient should be zero for no distortion of the signal, the variance should be the same for both cases. Because both amplifiers were built on different chassis and shielded from each other, the coupling capacity between the amplifiers must have been very small. The zero for balance of the recorder was then determined by grounding

the inputs to both amplifiers. Because  $|\bar{v}_0^2|$  and  $|\bar{v}_2^2|$  are functions of the equivalent noise resistance of the amplifiers,  $R_n$ , it is desirable to make  $R_n$  as small as possible.  $R_n$  for each amplifier was approximately 770 ohms at 300° K over a band width of 3 to 7 kc/s. This was derived by measuring the recorder deflection (or the squared r.m.s. voltage at the inputs to the multiplier) for  $|\bar{v}_0^2|$  and  $|\bar{v}_2^2|$  for various input resistances to the amplifiers at room temperature. For a band width of 3 to 12 kc/s the equivalent noise resistance of the amplifiers was 650 ohms. If one assumes that the flicker noise is proportional to  $1/f$ , then the equivalent noise resistance of the amplifiers at high frequencies is approximately 340 ohms. Therefore, flicker noise was the main contribution to  $R_n$  between 3 and 7 kc/s.

#### 4. Errors Due to Mismatch of the Time Constants in the $\pi$ Network

Equations (4) and (5) were derived under the condition that  $(\omega\tau_i)^2 \ll 1$  or that all the  $\tau$ 's are equal. If this does not hold, then equation (4) for  $T_0 = T_2$  is modified and one gets:

$$(4a) \quad \frac{T_0(R_0+R_2)}{T_1-2T_0} = R_1 \frac{1+(\omega^2\tau_0\tau_2)/(T_1-2T_0)\{T_1-T_0\tau_1[(1/\tau_0)+(1/\tau_2)]\}}{1+(\omega\tau_1)^2}$$

If

$$T_1 \gg T_0 \quad \text{and} \quad T_1 \gg T_0\tau_1\left(\frac{1}{\tau_0} + \frac{1}{\tau_2}\right),$$

one obtains:

$$(4b) \quad \frac{T_0(R_0+R_2)}{T_1-2T_0} \simeq R_1 \frac{1+(\omega\tau_1)^2(\tau_0\tau_2/\tau_1^2)}{1+(\omega\tau_1)^2} = R_1 f(\omega, \tau_1).$$

At helium temperatures it is then sufficient to make  $\tau_0\tau_2 \simeq \tau_1^2$ . The deviation of  $f(\omega, \tau_1)$  from unity will increase with increasing frequency. If both  $\tau_0$  and  $\tau_2$  are 10% larger than  $\tau_1$ , then the error at the upper half power frequency is less than 1%. The average error is smaller, because for lower frequencies the error decreases and  $\tau_1$  was always adjusted between  $\tau_0$  and  $\tau_2$ . For a systematic error in adjusting  $\tau_1$  the fractional error in the noise temperature is almost a constant in the liquid helium range.

#### 5. A-c. Resistance of Thermometer Elements

The deviation of the resistance of  $R_0$ ,  $R_1$ , and  $R_2$  in the audio-frequency range from their d-c. value was estimated to be approximately 0.1% (see above).

#### 6. Response of the Integrator

In the case of a narrow square noise band of width  $B$  and uniform spectral intensity a RC integrator of integration time  $\tau$  will measure with a relative error of a single measurement,  $\beta$ , (Burgess 1951):

$$(8) \quad \beta = \frac{[(A-\bar{A})^2]^{\frac{1}{2}}}{\bar{A}} = (2B\tau)^{-\frac{1}{2}},$$

where  $\bar{A}$  is the deflection of the recorder due to the d-c. component of the signal and  $[(A-\bar{A})^2]$  the mean-square deviation of the recorder due to the signal.

For  $B = 4$  kc/sec and  $\beta = 5 \times 10^{-3}$  (0.5%)  $\tau$  should be at least 5 seconds. Integration times from 22.5 to 90 seconds were used. The band widths of both amplifiers were approximately equal.

#### 7. Lead Corrections

If one assumes that the temperature of the leads going to  $R_0$  and  $R_2$  are at room temperature (worst possible case), then the lead resistance should be less than 0.3 ohm for errors smaller than 0.5%, a requirement not difficult to satisfy.

#### 8. Pickup

To avoid errors due to 60 c.p.s. pickup the lower half power points of the amplifiers were determined at approximately 5 kc/sec. Because no shielded room was available experiments could be performed only at night with fluorescent light, thyatron rectifiers, d-c. motors, etc. turned off. Although the amplifiers were protected against shock, audio noise was easily picked up. The voltages were constantly monitored oscillographically at the inputs of the multiplier, to check the randomness of the noise.

### IV. EXPERIMENTAL RESULTS AND DISCUSSION

Table I shows the boiling points of liquid oxygen and liquid nitrogen measured with approximately 4.48 k $\Omega$  metal film deposit resistors ( $R_0$  and  $R_2$ ) at barometric pressure with an integration time of 90 seconds. They were

TABLE I

Temperatures derived from the vapor pressure,  $T$ , measured noise temperatures,  $T_0$ , and their ratios for the boiling points of oxygen and nitrogen at barometric pressure

$T$ , °K	$T_0$ , °K(meas.)	$T_0/T$
90.23	$90.26 \pm 0.06$	$1.000 \pm 0.001$
77.33	$77.25 \pm 0.08$	$0.999 \pm 0.001$

found to be within 0.2% of the temperatures determined from the vapor pressure. The results of the noise-temperature measurements at helium temperatures are shown in Fig. 3. Because, as pointed out in the introduction, the noise power of the real part of an impedance is a universal function of frequency and temperature, any systematic deviation of the noise-temperature can only be due to experimental error of the equipment. The plot in Fig. 3(a) can be fitted best by an equation of the form:

$$(9) \quad \frac{T_0}{T} = \frac{A}{T} + b,$$

where  $A = 0.385^\circ$  K and  $b = 1$  for this thermometer. The term  $A/T$  can be explained due to errors which can be represented by noise-current sources in shunt with the  $\pi$  network. Equation (7) shows that this error must be proportional to  $1/T$  and the constant of proportionality is  $[e(I_1 + I_2 + I_3) + 2k\alpha T_1/R_g]R_0/2k$ . If errors due to  $k_g$  are neglected, then in the above experi-

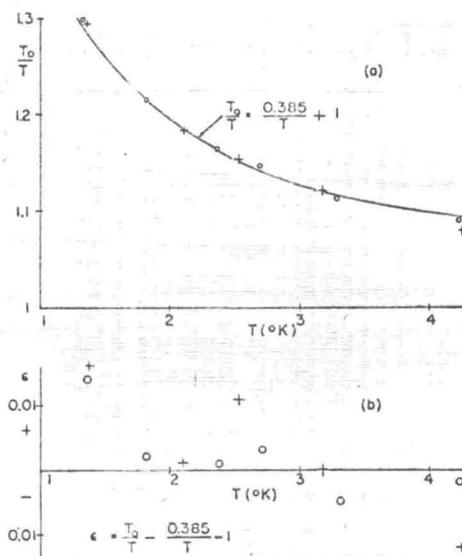


FIG. 3. (a) The experimental results at helium temperatures.  $T_0$  is the noise temperature calculated from equation (5) and  $T$  the temperature determined from the 1958 helium vapor pressure scale.

(b) The deviation  $\epsilon$  of  $T_0/T$  from the equation  $A/T+1$  with  $A = 0.385^\circ \text{K}$ .  $\circ$  represents measurements with an integration time of 90 seconds and  $+$  with 67.5 seconds.

ment  $I_1 + I_2 + I_3 = 3.7 \times 10^{-9}$  amperes. The measured grid current  $I_1 - (I_2 + I_3)$  was approximately  $2.6 \times 10^{-9}$  amperes, which shows that shot noise due to the grid current is the main limitation of the thermometer. At 15 kc/s  $R_g$  was measured to be larger than  $10^7$  ohms, and because the noise temperature  $T_g = \alpha T_1$  of  $R_g$  is unknown the contribution due to the second term is uncertain. If  $I_2$  and  $I_3$  are neglected compared with  $I_1$  then one can conclude that  $R_g/\alpha \simeq 47 \times 10^6$  ohms.

At helium temperatures equation (4b) applies, and over this temperature range a systematic error in adjusting  $\tau_1$  gives a fractional error in the noise-temperature which is essentially a constant. This means that  $b$  in the equation (9) is not unity. If  $\tau_0\tau_2/\tau_1^2 = \text{constant} < 1$  for all the measured points between 1.3° K and 4.2° K, the curve in Fig. 3(a) will shift down.

In general it will be necessary to measure two known temperatures to calibrate a thermometer of the above kind. These measurements will determine  $A$  and  $b$  and when  $T_0$  is measured the absolute temperature,  $T$ , can be calculated. However, if one is certain that no systematic error is made in balancing the  $\tau$ 's, or if  $(\omega\tau_i)^2$  can be neglected with respect to unity then  $b = 1$ , and only one known temperature is necessary to calibrate the thermometer. Figure 3(b) shows the deviation  $\epsilon$  of  $T_0/T$  from the equation  $(A/T)+1$  with  $A = 0.385^\circ \text{K}$  plotted as a function of  $T$ . The calibrated thermometer measures temperatures accurately within  $\pm 1\%$  between 1.3° K and 4.2° K.

This experiment makes use of the correlation of voltages from three independent noise sources at different temperatures to determine the temperature of one (or two) noise sources. This method has the advantage that it eliminates

any switching device at the input of the amplifier. The requirements of this method are that for good absolute accuracy of the thermometer the amplifiers, the multiplier, and the integrator must be linear and that  $T_1 > (T_0 + T_2)$ . At present the main limitation of the absolute accuracy at low temperatures is shot noise generated at the grids of the first stages of the amplifiers. In principle, this method can also be used to measure high temperatures.  $R_1$  could be a fixed resistor at the unknown temperature, and  $R_0$  and  $R_2$  could be kept at room temperature and one or preferably both of them be variable. At high temperatures errors due to shot noise can be neglected. When  $Z_1$  is made infinite and  $R_0$  and  $R_2$  are replaced by two antennas which are located apart from each other, then one has in principle a radio interferometer of the kind developed by Brown and Twiss (1954).

In this experiment it was demonstrated that it is possible and feasible to measure low temperatures absolutely by making use of the thermal fluctuations of voltage across an impedance. Work will continue at this university to improve the accuracy of the noise thermometer, and to derive an absolute temperature scale in the liquid helium region.

#### ACKNOWLEDGMENTS

The author is most grateful to acknowledge many helpful discussions with Dr. J. B. Brown regarding the low temperature aspects of this work and with Professor R. E. Burgess regarding matters of noise. The author also wishes to thank: Dr. J. B. Garrison for his suggestion of correlating voltages from noise sources at different temperatures, Professor A. Van der Ziel for his suggestion of the tube for the first stage to Dr. J. B. Brown, Dr. J. M. Daniels for stimulating this research, Mr. H. H. M. Zerbst for the construction of the cryostat, and the National Research Council, Canada, for a studentship and the financial support of this project.

#### REFERENCES

- AUMONT, R. and ROMAND, J. 1954. *J. phys. rad.* **15**, 585.  
 BAKKER, C. J. and HELLER, G. 1939. *Physica*, **6**, 262.  
 BERNAMONT, J. 1937. *Ann. Physik*, **7**, 71.  
 BITTEL, H. and SCHEIDHAUER, K. 1956. *Z. angew. Phys.* **8**, 417.  
 BOYLE, W. S. and BROWN, J. B. 1954. *Rev. Sci. Instr.* **25**, 359.  
 BRICKWEDDE, F. G. 1959. Kamerling Onnes Conference, Leiden, June 23-28, p. 128.  
 BROWN, J. B. and MACDONALD, D. K. C. 1946. *Phys. Rev.* **70**, 976.  
 BROWN, R. H. and TWISS, R. Q. 1954. *Phil. Mag.* **45**, 663.  
 BURGESS, R. 1941. *Proc. Phys. Soc. (London)*, **53**, 293.  
 ——— 1951. *Phil. Mag.* **42**, 475.  
 CADE, C. M. 1958. *J. Roy. Aeronaut. Soc.* **62**, 805.  
 CHRISTENSON, C. J. and PEARSON, G. L. 1936. *Bell System Tech. J.* **15**, 197.  
 COOK, R. K., GREENSPAN, M., and WUSSLER, P. G. 1948. *Phys. Rev.* **74**, 1714.  
 DICKE, R. H. 1946. *Rev. Sci. Instr.* **17**, 375.  
 DICKE, R. H. and BERINGER, R. 1946. *Astrophys. J.* **103**, 375.  
 DICKE, R. H., BERINGER, R., KYHL, R. L., and VANE, A. B. 1946. *Phys. Rev.* **70**, 340.  
 VAN DIJK, H. and DURIEUX, M. 1958. *Physica*, **24**, 920.  
 GARRISON, J. B. and LAWSON, A. W. 1949. *Rev. Sci. Instr.* **20**, 785.  
 GERJUOY, E. and FORRESTER, A. T. 1947. *Phys. Rev.* **71**, 375.  
 LAWSON, A. W. and LONG, E. A. 1946. *Phys. Rev.* **70**, 220, 977.  
 NATIONAL PHYSICAL LABORATORY. 1957. Annual report (Her Majesty's Stationery Office, London), p. 84.  
 NYQUIST, H. 1928. *Phys. Rev.* **32**, 110.  
 SPENKE, E. 1939. *Wiss. Veröffentl. Siemens-Werke*, **18**, 55.  
 VAN DER ZIEL, A. 1954. *Noise* (Prentice-Hall, Inc., New York), p. 9.