ance its effect on the output of the reference unit. The variation of the dynamic resistance with time was found to be small enough to be completely neglected.

3. Likewise, the temperature coefficient showed no tendency to vary with time.

4. The most severe test on the diodes was the extreme temperature exposure. The diodes were exposed to −55 C and 100 C, with checks at 25 C between exposures. This indicated a slight hysteresis effect on diode output, with the low temperature exposure increasing voltage at 25 C and the high temperature decreasing voltage. The cause of this effect is unknown, though it may be due to adsorption and desorption of impurities on the silicon junctions from the surrounding material.

This severe test produced one of the few failures, as one diode shifted 0.18% from its original breakdown voltage.

5. Five of the *1N430* diodes were subjected to 14,800 thermal shocks over a 6-day period. The thermal shock consisted of pulsing the diodes at their rated power dissipation, which is well above their normal operating level. The effect here was negligible, indicating that the diodes are conservatively rated.

6. In order to test repeatability, diodes were switched on and off over 600 cycles, the voltage during each "on" period being recorded automatically. Results indicated that the diode's ability to produce the same voltage repeatedly is comparable to that of a standard cell.

7. Five diodes were tested in high humidity as outlined in military specification *MIL E-5272A*. The results showed a maximum voltage variation 0.012% and average of 0.010%. Humidity evidently has negligible effect.

8. Diodes were subjected to vibration in three planes with the following frequencies and magnitudes:

Frequency cps	Total Travel or Acceleration
5 to 10	40 mils
10 to 75	16 mils
75 to 500	5 g*

* Gravitational acceleration.

These tests indicated no effect on diode voltage.

However, it was discovered during the vibration tests that the diode voltages are slightly sensitive to diode position. A change of 0.018% resulted from a 90-degree change in orientation. The presumed reason for this was the change in heating effect caused by the flow of the silicone oil in which these diode junctions were immersed. As the diodes are applied in a recorder, the position influence is of no consequence, as the diode's orientation is fixed.

9. A 500-volt potential was applied to five diodes from case to one terminal. No failures were found, and diode voltage was virtually unaffected.

Conclusions

The results of these tests indicated that the diodes meet the manufacturer's specifications and that they further appear to be stable over long periods. They also withstand many severe environmental conditions. On the basis of these data, the diode has been used in the precision reference described in this paper, which in turn is being supplied as a part of the General Electric Company's strip chart recorder.

Thermal Voltage Converters for Accurate Voltage Measurements to 30 Megacycles Per Second

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Synopsis: Thermal voltage converters, each consisting of a resistor in series with a thermoelement in a coaxial line, have been developed for measurements of rms voltages of 1 to 200 volts at frequencies from 3 cps (cycles per second) to 30 mc (megacycles). An accuracy of 0.1% or better may be obtained by a-c–d-c transfer techniques up to at least 10 mc and 0.2% at 30 mc.

A THERMAL VOLTAGE converter, according to ASA Standards,[1] is a thermoelement of low current input rating with an associated series impedance or transformer, such that the emf (electromotive force) developed at the output terminals gives a measure of the voltage applied to the input terminals. Thermal voltage converters containing thermoelements in series with wire-wound resistors can be used to make highly accurate voltage measurements at audio and ultrasonic frequencies.[2,3] The frequency range of such voltage converters is limited primarily by the residual reactances of their wire-wound resistors, but tests have indicated that for some of them good performance might be expected to frequencies approaching 1 mc.

This paper describes thermal voltage converters of low and computable reactance that have been developed at the National Bureau of Standards to meet the need for determining the frequency limit of such instruments. Single-range converters with deposited-carbon resistors have been constructed with ranges of 1 to 200 volts. Each has a frequency influence less than 0.1% to 10 mc and less than 0.4% at 30 mc. These rms voltage converters may also be used to calibrate 1/2% r-f (radio-frequency) thermocouple voltmeters which are now commercially available, and, with sine wave generators, could be used to calibrate electronic voltmeters as well.

Description and Construction of Converters

The r-f thermal voltage converters make use of the transfer principle,[2] in which a direct voltage is substituted for the alternating voltage to be measured. The direct voltage is adjusted to give the same output emf of the thermoelement that was obtained with the alternating

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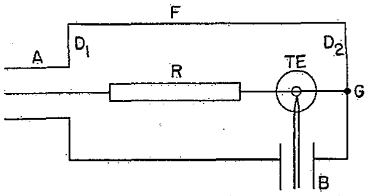

Fig. 1. Thermal voltage converter

R=Film-type resistor 1/8 in. diameter, 2 in. long
TE=Thermoelement
A=Coaxial input connector, GR874PB
B=Two-pin output connector, AN10SL
D_1, D_2=Circular brass disks, 3/16 in. thick, secured to F with 4 2-56 brass screws
F=Cylindrical brass shield, 2 in. diameter, 4.25 in. long
G=Cross wire at center of D_2 (see text)
Note: Plane of thermocouple leads at right angles to axis of F

voltage applied, and is measured with a potentiometer or other suitable means. Thus only good short-time stability, high precision of reading, and small known frequency influence are required of the transfer standard.

Each converter consists of a cylindrical deposited-carbon resistor in series with a uhf (ultrahigh frequency) thermoelement having a short straight heater in line with its supports, coaxially mounted in a brass cylinder, as shown schematically in Fig. 1. The residual reactances are much smaller than those of wire-wound resistors, and can be computed at least approximately, so that the frequency errors can be estimated. The frequency errors of the uhf thermoelements as current converters are believed to be small to over 100 mc.

The dimensions of the converters and additional data are given in the caption of Fig. 1. Each converter is assembled by first soldering the resistor, R, to the thermoelement, TE, and to the coaxial input connector, A, which is mounted in disk, D_1. This disc is then fastened to the cylinder, F, and the two thermocouple leads are soldered to the 2-pin output connector, B. Disk D_2, which has a small hole with a cross wire at G, is then fastened to F and the free end of the heater of the thermoelement is soldered to the cross wire. For clarity both thermocouple leads are shown in the figure. However the plane of the thermocouple leads and the pins of the output connector are actually at right angles to the axis of the cylinder so that minimum emf is induced in the output circuit. In use F must be grounded through the input connector.

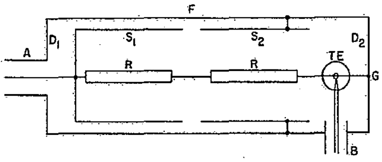

Fig. 2. Voltage converter with compensating shields

S_1=Cylindrical brass shield, 2 in. diameter with one brass end-plate
S_2=Cylindrical brass shield, 2 in. diameter both ends open, axially adjustable (see text)
Other symbols same as Fig. 1 except that F is 2.5 in. diameter and 7.5 in. long
Note: Plane of thermocouple leads at right angles to axis of F

The 100- and 200-volt converters contain two resistors and two cylindrical inner shields, S_1 and S_2, as shown in Fig. 2, to reduce the effect of the distributed capacitance from the resistors to the outer cylinder. This considerably extends their frequency range. Shield S_2 is centered in F by a narrow ring, and is fastened to F by three equally spaced screws. Slots in F make axial adjustment of S_2 possible. The end-plate of S_1 is soldered to the input lead and to the resistor in assembly and this shield is fastened to D_1 by small insulators. The assembly is otherwise similar to that described for the other converters. The 50-volt converter has a single resistor and a fixed inner shield like S_1 in a cylinder of the dimensions given in the caption of Fig. 1.

Additional information on the voltage converters is given in the first three columns of Table I. The commercially available deposited carbon resistors are 1/8 inch in diameter and 2 inches long, and are vacuum sealed within a 3/16-inch-diameter glass cylinder. Some resistors of a different construction showed unaccountable a-c–d-c errors above 10 mc when used in earlier converters. The 5- and 10-ma uhf thermoelements, each with colinear supports and heater wire, are also commercially available, with an output voltage of about 7 mv (millivolts) at rated current. Each is in an acorn-shaped evacuated glass bulb, and has a small bead between the heater and hot junction of the thermocouple to insulate them electrically but not thermally.

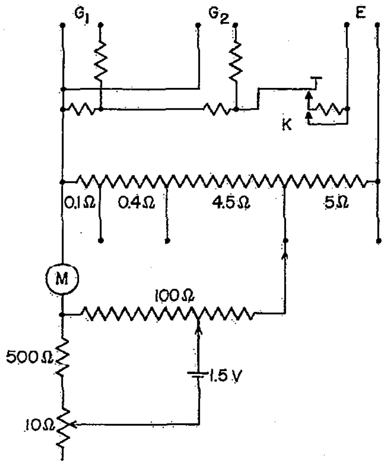

Fig. 3. Circuit of Lindeck potentiometer

M=1.5-ma d-c milliammeter
K=Thermofree key
E=Emf terminals, AN10SL
G_1, G_2=Galvanometer terminals, AN10SL
Note: All fixed resistors of manganin, accuracy +0.2%

A Lindeck potentiometer rather than a millivoltmeter is connected to the output emf of the converter to provide high resolution. A circuit diagram is shown in Fig. 3. The potentiometer has ranges of 0.15, 0.75, 7.5, and 15 mv. The two lowest ranges are used for sensitivity checks. With a galvanometer having a sensitivity of 200 mm (millimeter)/μa (microampere) it provides a selected resolution of either 2 or 10 μv (microvolts) per mm deflection. The potentiometer is completely shielded, and a 2-conductor shielded cable connects the output of the converter to the terminals marked E in the figure. The advantages of this potentiometer are its low thermal emf (less than 1 μv) and its freedom from drift (much less than 0.01%/minute under ordinary laboratory conditions).

Theory

Because of the geometry, the resistor, R, in the cylinder of each low-voltage converter (without inner shields) may be represented as a transmission line of length, ℓ, with a uniformly distributed series impedance of z ohms per unit length and a uniformly distributed shunt ad-

Table I. Voltage Converters

	Thermoelement		
Rated Voltage, Volts	Rated Current, Ma	Heater Resistance, Ohms	Series Resistor, Kilohms
1	5	90	0.2
3	5	90	0.5
5	5	90	1
10	5	90	2
20	10	25	2
50	10	25	5
100	10	25	10*
200	10	25	20*

* Two equal resistors in configuration of Fig. 2.

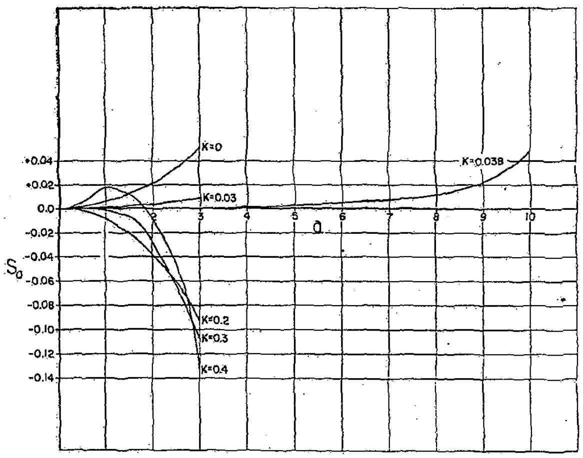

Fig. 4. Computed a-c-d-c difference as a function of the parameters a and k

mittance of y mhos per unit length. The line is terminated by the heater of the thermoelement. We are interested in the magnitude of the transimpedance $Z_c = V_i/I_o$ where V_i is the input voltage being measured and I_o is the current through the heater. If the heater resistance, R_h, is much less than that of the resistor, R, we may to a first approximation consider this a short-circuited line. It will be apparent later that this is not a drastic approximation at low frequencies since we are concerned only with the effect of the line reactance on Z_c. Then by ordinary steady-state transmission-line theory,

$$Z_c = \frac{Z}{\sqrt{ZY}} \sinh \sqrt{ZY} \qquad (1)$$

where $Z = z\ell = R + j\omega L$, and $Y = y\ell = j\omega C$ and R, L, and C are the total resistance, series inductance, and shunt capacitance of the line. We are interested in the low-frequency range in which the effects of the reactances are small.

We may define the parameters $a = \omega CR$ and $b = \omega L/R$. If each of these is less than unity the hyperbolic function may be approximated by the first three terms of its series expansion, so that

$$Z_c = Z\left(1 + \frac{ZY}{6} + \frac{(ZY)^2}{120} + \dots\right)$$

Then if all terms in $a^n b^m$ for which $m + n > 3$ are discarded we find that

$$Z_c \approx R(1 + jb)\left(1 - \frac{ab}{6} - \frac{a^2}{120} + \frac{ja}{6}\right)$$

and, to the same order,

$$|Z_c| \approx R\left(1 + \frac{a^2}{90} + b^2 - \frac{ab}{3}\right)^{1/2} \approx$$

$$R\left(1 + \frac{a^2}{180} + \frac{b^2}{2} - \frac{ab}{6}\right) \qquad (2)$$

The a-c-d-c difference of a voltage converter is defined as

$$S = \frac{V_{ac} - V_{dc}}{V_{dc}} \qquad (3)$$

where V_{ac} and V_{dc} are the rms alternating and direct voltages required to obtain the same response (output emf) of the converter. If the thermoelement has no a-c-d-c difference and if we define $k = b/a$, this becomes

$$S_o = \frac{|Z_c| - R}{R} \approx \frac{a^2}{2}\left(k^2 - \frac{k}{3} + \frac{1}{90}\right) \qquad (4)$$

where S_o signifies that other possible causes of a-c-d-c differences are neglected.

The relation makes it possible to estimate S_o to this approximation very simply. For the cylindrical construction of Fig. 1 with a cylindrical unspiraled resistor, $L = 0.012\ell M$ microhenry and $C = 0.61\ell/M$ picofarad, where $M = \log_{10}(g/h)$ and g and h are the diameters of the cylinder and resistor, respectively, and ℓ is in inches. Thus numerically, $k = 1.9 \times 10^4 (M/R)^2$ and $a = 3.8 \times 10^{-12} f\ell R/M$, where f is the frequency.

For example if $R = 2{,}000$ ohms, g and h are 2 in. (inches) and 1/8 in., and $\ell = 2.0$ in., $S_o = +0.001$ (+0.1%) at 40 mc.

It is apparent from equation 4 that to this approximation certain values of k should make $S_o = 0$. These are $k_1 = 0.038$ and $k_2 = 0.30$. The numerical values of resistance required are $R_1 = 710M$ and $R_2 = 250M$. Unfortunately the logarithmic relationship for M permits little range in R for reasonable values of g and h, for if g is greater than the length of the resistor, end effects may become pronounced.

It is of interest to extend the analysis to higher values of the parameter, a. This has been done by solving equation 1 for Z_c with the aid of Kennelley's tables and graphs of hyperbolic functions having complex arguments,[4] and then computing $S_o = (|Z_c| - R)/R$. The results are shown in Fig. 4. It is rather striking that the first solution of equation 4, $k_1 = 0.038$, results in reasonably small a-c-d-c differneces (<5%) to $a = 10$, a range much greater than that permitted by the initial assumptions.

For low-voltage converters the effect of the heater resistance R_h cannot be neglected. To the next approximation the heater can be considered as a lumped resistance termination for the transmission line. Then from steady-state transmission-line equations,

$$Z_c = R_h \cosh \sqrt{ZY} + \frac{Z}{\sqrt{ZY}} \sinh \sqrt{ZY} \qquad (5)$$

By expanding the hyperbolic functions and discarding higher order terms as before (for $a < 1$ and $b < 1$) we find that if $R_h < R$

$$S_o = \frac{|Z_c| - R_t}{R_t} \approx \frac{1}{2}\left(\frac{a}{1+m}\right)^2 \left(k^2 - Ak + \frac{B}{6}\right) \qquad (6)$$

where $R_t = R + R_h$, $R_h/R = m$, $A = m^2 + 2m/3 + 1/3$ and $B = m^2 + 2m/5 + 1/15$.

Table II. Comparative A-C-D-C Differences of Voltage Converters

Voltage Range			Comparative A-C-D-C Difference, D, Per Cent						
Converter A	Converter B	Applied Volts	0.1 mc	1 mc	5 mc	10 mc	20 mc	30 mc	40 mc
1	3	1	+0.01	0.00					−0.08
1	3	1.5		+0.01	−0.01	0.00	−0.02	−0.03	−0.06
3	5	2		0.00					−0.05
3	5	3	0.00	0.00	0.00	−0.01	−0.01	−0.03	−0.04
5	10	3		0.00					+0.14
5	10	5	0.00	0.00	−0.01	+0.01	+0.02	+0.07	+0.15
10	20	6		0.00					−0.02
10	20	10		0.00		0.00	0.00	−0.01	−0.02
20	50	15	0.00	0.00					−0.04
20	50	20				0.00	0.00	−0.01	−0.04
20	100	20	0.00	0.00	+0.02	+0.07	+0.24	+0.33*	+0.17
50	100	50		0.00				+0.33	
50	200	50	+0.01	0.00	−0.02	−0.06	−0.04	+0.19*	+0.57
100	200	90		0.00				−0.14	

Note: $D = 100(S_B - S_A)$, where S is defined by equation 3, and the subscripts refer to converters A and B.
* Additional comparisons made at 25 and 35 mc.

The values of S_o for the 1- to 20-volt converters have been calculated by equation 6 at a frequency of 40 mc, at which a and b are still less than unity. The results are given in the last column of Table II.

When $k<0.038$, distributed capacitance from the resistor to the cylinder predominates. At a given frequency and geometry, the resultant error is proportional to the square of the resistance. It can be minimized by the construction shown in Fig. 2 in which two inner cylindrical shields are used, with one connected to the input lead. Thus there are now two transmission lines in series. If $R_h<<R$, application of transmission line equations, with careful attention to signs, gives for the desired transimpedance,

$$Z_c=\sqrt{\frac{Z_1}{Y_1}}\tanh\sqrt{Z_1Y_1}\cosh\sqrt{Z_2Y_2}+\sqrt{\frac{Z_2}{Y_2}}\sinh\sqrt{Z_2Y_2} \quad (7)$$

where the subscripts 1 and 2 refer to the left and right hand lines (resistors and shields) of Fig. 2, and the resistance of the thermoelement is neglected.

If $Z_1=Z_2=Z$ and $Y_1=Y_2=Y$ we have

$$Z_c=\frac{2Z}{\sqrt{ZY}}\sinh\sqrt{ZY}$$

Thus the transimpedance is twice that of either line, and the a-c–d-c difference, S_o, will be that of half the total line. The parameter, a, of equation 4 will then be one-fourth that for a line of the same dimensions without inner shields. Thus at a given frequency for which $a<1$ the use of the double shield rather than a single cylinder of the same diameter should reduce the frequency error, for resistors of the same value and dimensions, by a factor of 16.

However, more detailed analysis indicates that even further improvement may be possible. For these converters $k<<0.038$, so that the series inductance of each line may be neglected. By expanding the hyperbolic functions of equation 7 and discarding higher order terms it can be shown by lengthy and rather tedious algebraic manipulation that $S_o\approx 0$ when $l_1/l_2\approx 1.032$, where l_1 and l_2 are the lengths of the left and right hand lines of Fig. 2, and $a<1$.

For the convenient dimensions shown in Fig. 1, the parameter, a, of each low-voltage (up through 20 volts) converter now being used is low enough that it has not been necessary to proportion the converters for minimum error in accordance with equation 6. The higher voltage elements are constructed with dual shields, with the grounded shield axially adjustable. This shield is set to give minimum frequency error as explained in the next section.

A useful theoretical study of coaxial lines, terminated by resistors, was published by Crosby and Pennypacker.[5] They show conditions for minimizing the input reactance.

Tests

Although long-time stability is not required of these converters, fluctuations or drifts in emf for the short time between the a-c use and the d-c calibration must be less than the desired accuracy. Such changes can arise from self-heating effects and ambient temperature changes, and from thermal emfs and other changes in the Lindeck potentiometer. Tests have shown that the self-heating of the carbon resistors, which have a load coefficient of about 1% per watt, is the largest source of drift. The change in resistance is very nearly exponential, with a time-constant of about 2 minutes. Since d-c calibrations can easily be made within 30 seconds of the a-c readings, this self-heating error is not significant in a-c tests if a short warm-up period is allowed. It is almost completely eliminated by the procedure used for a-c–d-c transfer tests. The effect of ambient temperature changes—the thermoelements have temperature coefficients up to 0.1%/C (degrees centigrade)—should also be insignificant in a laboratory with reasonable temperature control.

A great advantage of thermoelements for a-c–d-c transfer measurements is the almost complete electrical isolation of the input and output circuits. The uhf thermoelements have a small electrically insulating bead between the heater and hot junction of the thermocouple to eliminate conductive coupling. To minimize mutual inductance the plane of the thermocouple leads is at right angles to the heater and its colinear supports. Tests showed that at 4 mc the induced a-c voltage in the output circuit of each thermoelement was less than 20 μv, the resolution of the detector used. Induced currents in the thermocouple circuit can cause errors by joule heating of the thermocouple, but calculations indicate this should not be significant if the induced voltage is less than a few millivolts.

The shield of the Lindeck potentiometer provides reasonable immunity from induced fields. In some tests at 10 mc a current of 2 ma from the shield to ground through the lead from the potentiometer to the converter caused no significant error.

For transfer measurements the most important requirement is that the a-c–d-c difference of each of these converters be known to the full accuracy desired. The general principles on which such determinations are based have been given.[2] In the frequency range studied, the major error of each of these converters is caused by the reactance. For a given converter this error should be independent of voltage level. Thus, it was feasible to evaluate the relative errors by intercomparing converters of adjacent voltage ranges to determine their differences in frequency response. A complete series of such comparisons was made at two voltage levels for each pair of converters, at frequencies up to 40 mc. In each comparison the two converters were connected in parallel to a coaxial lead through a tee fitting (*GR 874*), and a shielded potentiometer was connected to each output. Each potentiometer was adjusted for zero deflection at the test voltage. The converters were then supplied in succession with alternating, direct, reversed-direct, and alternating voltage. Each voltage was adjusted to produce the same emf of the higher range converter and the deflection of the galvanometer connected to the other converter was observed. From the differences in emf, directly determined from these differences in deflection, the difference in the frequency response of the two converters was determined.[2] In these tests the movable inner shields of the 100- and 200-volt converters were adjusted for best performance over the desired frequency range, by comparison with the 20- and 50-volt converters. The errors of these adjustable converters were found to be complicated functions of the frequency and shield position.

The results of these intercomparisons from 0.1 to 40 mc are given in Table II. They show that for each pair of converters the relative a-c–d-c differences were independent of the applied voltage to 0.02% or less, and were less than 0.4% up to 30 mc. For the low-voltage converters they were less than 0.05% to 20 mc without exception and without evidence of systematic errors.

The relative a-c–d-c differences of most of the thermoelements used in the voltage converters were also determined before the thermoelements were installed, by making similar a-c–d-c intercomparisons as current-measuring elements at 40 mc. For these tests the two thermoelements were connected in series along the axis of a brass cylinder having the same dimen-

Table III. Results of Test of 1-Volt Voltmeter

Frequency, Mc	Applied Voltage,* Volts
1	0.997
10	0.998
30	0.998
100	0.999
200	0.982
300	0.945
400	0.883

*For same reading of millivoltmeter at each frequency

sions as in Fig. 1 but with a coaxial input connector at each end and with two 2-pin output connectors. A split cylinder with one part readily removable facilitated changing thermoelements. The input was applied to one connector with the other short-circuited. Rough calculations indicated that at 40 mc the current should change by about 0.5% along the transmission line formed by the heaters of the thermoelements in this cylinder, but that the distribution should not be greatly dependent on the resistance of the heaters, less than 100 ohms each. Therefore, two determinations of relative a-c–d-c differences were made with each pair of thermoelements, with first one end then the other of the cylinder short-circuited. For each pair the two determinations differed by about 0.4% at 40 mc, but in each case their algebraic average was less than 0.02%.

These calculations and tests also provide assurance that even at 40 mc the current along the heater of a single thermoelement terminating a voltage converter is well within 0.1% of the value at the mid-point of the heater.

The 1-volt converter was compared at rated voltage with a wire-wound thermal voltage converter of known a-c–d-c difference at 3 cps and 20 kc, with observed differences of +0.02% and 0.00% respectively.

The response of the 1-volt converter, with a shielded d-c millivoltmeter connected to its output, was determined to better than 1% at frequencies from 1 to 400 mc by the bolometer bridge of Selby and Behrent,[6] with the results shown in Table III. It is evident that the frequency influence is very small to 100 mc. It increases rapidly at higher frequencies, becoming −5.2% at 300 mc. The calculated a-c–d-c difference at 300 mc by equation 6 is only −0.9%; this converter has a 1/4-in.-diameter unsealed resistor. Some of the discrepancy may be accounted for by the voltage rise in the connector. A type *N-UG58/U* input connector was substituted for the type *874* for these tests.

As a check on equation 6 at larger a-c–d-c differences, the 50-volt converter was tested before its inner shield was installed. The measured a-c–d-c difference at 40 mc was +1.3% and was accurately proportional to the square of the frequency. The computed values were 40% smaller, indicating that the effective length of the resistor, the end effect, was 1.2 times the actual length. At 40 mc the measured a-c–d-c difference was changed by less than 0.02% when the resistor was mounted 3/32 inch off the axis of the cylinder, indicating that exact centering is not critical even when the errors are large.

The intercomparisons of Table II show that the a-c–d-c differences of the five low-voltage converters without inner shields, and with 1- to 20-volt ranges, are all equal to better than 0.05% to more than 20 mc. At 40 mc they agree to 0.1% with the values calculated by equation 6. Values cannot readily be computed for the higher voltage elements with the inner shields. This unanimity between converters having such a wide range of resistors and different thermoelements gives good assurance against unknown sources of error. It is quite unlikely, but not impossible, that each converter would have the same a-c–d-c error. However the test of the 1-volt converter with the bolometer bridge provides most valuable additional assurance. The large errors of this converter above 100 mc decrease rapidly with decreasing frequency, well within the stated accuracy of the bridge measurements. For converters without inner shields almost all known causes of such errors, such as the effect of reactance, equation 6, skin effects in the resistor or thermoelement, etc., should cause a-c–d-c differences approximately proportional to the square of the frequency, over the range for which the errors are small. Thus the authors believe that the large measured errors above 100 mc can be extrapolated downward to lower frequencies to indicate with considerable confidence that the a-c–d-c difference of this converter is less than 0.2% at 40 mc and less than 0.1% below 30 mc.

Based on the foregoing consideration the authors assigned a value of zero to the a-c–d-c difference of the 1-volt converter to 40 mc, and then determined the a-c–d-c differences of all the other converters from the intercomparison data in Table II. The results, rounded to the nearest 0.05% to 10 mc and 0.1% to 40 mc, are given as observed values in Table IV.

Use

These converters are most conveniently used to measure the a-c–d-c difference or frequency influence of other rms instruments such as thermocouple voltmeters, which are now available with accuracies of 1/2% to 10 mc. A typical setup for this is shown in Fig. 5. The scale calibration of the voltmeter can then easily be checked on reversed direct current. The a-c–d-c difference tests are similar to the intercomparisons already described, and d-c calibration of the converter is not necessary once the scale factor of the Lindeck potentiometer is determined for each converter. This is the per-cent change in input voltage per centimeter change of galvanometer deflection.[2] Either direct or low-frequency alternating current may be used as the reference frequency and the test may be made rapidly and accurately. The results are only slightly affected by drifts in either instrument. At frequencies above about 20 mc a small lead correction may be necessary if the connectors between the junction plane and the two instruments are not electrically equal, but this is readily determined to the required accuracy.

For a-c measurements a d-c potentiometer of 0.1% accuracy or better is required to measure the d-c reference voltage. A deflection potentiometer and volt box, or an automatic self-balancing potentiometer ("digital voltmeter") should be convenient for this. For testing electronic voltmeters frequency-response measurements (differences in reading for

Table IV. A-C–D-C Differences of Voltage Converters

Rated Voltage, Volts	Per-Cent A-C–D-C Differences, 100S					
	Observed					Calculated
	to 5 mc	10 mc	20 mc	30 mc	40 mc	40 mc
1	<0.05	<0.05	0.0	0.0	0.0	0.0
3	<0.05	<0.05	0.0	0.0	−0.1	0.0
5	<0.05	<0.05	0.0	−0.1	−0.1	0.0
10	<0.05	<0.05	0.0	0.0	0.0	+0.1
20	<0.05	<0.05	0.0	0.0	0.0	+0.1
50	<0.05	<0.05	0.0	0.0	0.0	
100	<0.05	+0.05	+0.2	+0.3	+0.1	
200	<0.05	−0.05	0.0	+0.2	+0.5	

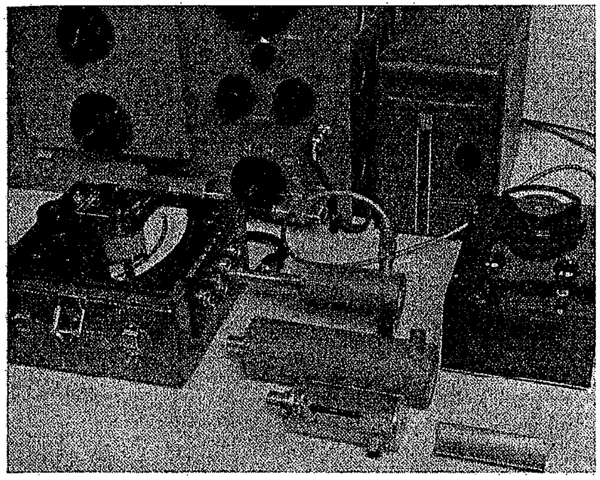

Fig. 5. 5-volt converter setup for a-c–d-c test of experimental thermocouple voltmeter. Lindeck potentiometer at right, double-shield converter and experimental split-shield element in foreground, a-c–d-c switch not shown

the same voltage at the test and reference frequencies) should be particularly convenient. The form factor and crest factor of the a-c sources must be within 0.1% of the values for a sine wave, 1.111 and 1.414 respectively, since most electronic voltmeters respond essentially to the average or crest (peak) values. Since these factors depend upon the phase angle as well as the magnitude of each harmonic it would ordinarily be necessary to make sure that the ratio of the magnitude of the nth harmonic to the fundamental does not exceed $0.1xn\%$ when an average-reading instrument is tested and 0.1% when a crest-reading instrument is tested. The results should then differ from those obtained with a sine wave by less than 0.1%.

An r-f generator of at least 5 watts output and good voltage stability is required but only moderate frequency accuracy and stability are needed. It is very difficult to construct broad-band generators of good wave form at this power level. However, a simple adjustable L/C (inductance capacitance) tuned circuit, with the instruments connected across the capacitor, can be used simultaneously to improve the wave form, match the impedance of the instruments to that of usual 50-ohm source, eliminate the capacitance loading of the instruments on the source, and provide the higher voltages often required. For these combined purposes the values of inductance and capacitance should be chosen so that $\omega L = 1/\omega C \approx \sqrt{R_1 R_2}$, where R_1 and R_2 are respectively the resistances of the source, including the inductor, and the load (instruments). For low voltages a 50-ohm resistor can be connected in series with the L/C circuit and the instruments and attenuators as needed can be connected in parallel with this resistor for improved wave form.

Conclusions

Cylindrical film resistors in series with a thermoelement in a coaxial line makes possible single-range thermal voltage converters that are useful as a-c–d-c transfer instruments over a very wide frequency range, 3 cps to at least 30 mc, with unusually high accuracy. They are inexpensive and easy to construct. Their frequency influence may be estimated by reasonably simple equations, with results which agree well with the measured values up to 40 mc. The voltage converters may be useful to considerably higher frequencies. The higher range converters require considerable power, up to 2 watts, and have a marked but short warm-up drift. These disadvantages could be reduced by using metal-film resistors of higher resistance with a 5-ma thermoelement, but this would very probably reduce the frequency range for the same attainable accuracy. The good performance of these converters was obtained with deposited-carbon resistors of a new type. Earlier converters with resistors of different construction showed discrepancies up to 0.5% at 40 mc. Further work is planned to determine the cause of these differences.

These voltage converters can be used quickly and easily to make a-c–d-c difference tests to determine the frequency influence of other rms instruments to 0.1% or better to at least 10 mc and to 0.2% at 30 mc. Direct a-c measurements are made by the transfer technique, which in most cases can be arranged for reasonable simplicity. With sources of suitable waveform, average-reading and crest reading instruments could also be calibrated if desired. In all of these applications the applied frequency need not be closely determined or held because of the flat frequency response of these voltage converters.

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Discussion

Morley J. Lush (Rawson Electrical Instrument Co., Cambridge, Mass.): I feel that the instruments described in this paper are a real contribution to the art of accurate voltage measurements at high frequencies. Although it is difficult to make resistors with low reactances, Mr. Hermach has shown that these can be obtained, and that voltmeters can be constructed which have a flat frequency response all the way from direct current out to the megacycle region. The frequency response will remain stable for long periods of time, so only d-c calibrations are needed, once the frequency response has been determined. I have found from my own work that accuracies of 1% can be obtained at frequencies up to 100 mc and now these instruments are available on the market. A precision of 0.1% can be obtained, but the absolute accuracy is limited by the lack of a primary standard. I have been told that the National Bureau of Standards expects to be able to offer 0.25% certifications by the end of 1960.

Other workers in this field have used a fixed or variable capacitor as the attenuator element in series with the thermocouple. It is possible to make an excellent low-loss capacitor using a micrometer screw for adjustment. A wide frequency range and wide voltage range can be obtained on one instrument. However, the voltmeter cannot then be used for d-c to a-c transfer measurements, since it has zero response at zero frequency. Indeed, the response is directly proportional to the frequency, and it is necessary to calibrate the voltmeter at each voltage and frequency for which it will be used.

It should be pointed out that connections to these voltmeters are a problem, as they are in all high-frequency apparatus. The use of coaxial connectors can be misleading, as any appreciable length of 50-ohm coaxial line will cause errors due to standing waves, unless the voltmeter input impedance is made exactly equal to the impedance of the line. Careful matching of the line impedance will certainly be necessary if voltmeters of this type are to be used at frequencies above 100 mc.

F. L. Hermach and E. S. Williams: Mr. Lush's remarks are appreciated. We believe these thermal voltage converters, by taking advantage of the powerful a-c–d-c transfer technique, should make possible a new order of accuracy in a-c voltage measurements up to at least 30 mc. Their usefulness will probably fall off rapidly at higher frequencies, except for the lower voltage ranges, up to perhaps 10 volts.

A major advantage of an a-c–d-c transfer standard is that its a-c–d-c difference is relatively permanent so that once evaluated, it should not ordinarily need to be redetermined. Thus, elaborate repeated a-c calibrations are not required. This and the ease and simplicity of constructing these converters should offset the extra labor of making the a-c to d-c transfer for each measurement.

We mentioned connection errors only briefly. Each converter is a high-impedance load at the end of a short coaxial line from the junction plane to the converter. If this line is a small fraction of a wavelength the voltage rise from the junction to the end of the line is approximately $50h^2\%$, where $h=\omega CZ_0$ and C and Z_0 are the total shunt capacitance and the characteristic impedance of the line. At 30 mc for a 2-inch length of typical 50-ohm line the correction is only 0.1%. It is offset by a similar correction if an equal line is used between the junction plane and the test instrument or load to be measured. At higher frequencies or for longer lines the correction can be large and this approximate formula may no longer be valid. In such cases, however, voltage measurements probably have meaning only with lines terminated in their characteristic impedance, so that the standing-wave ratio is close to unity.