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
thermocouple 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 50 mc (megacycles). An
accuracy of 0.1% or better may be obtained
by a-c-d-e-f-temperature techniques up to
at least 10 mc and 0.3% at 50 mc.

A thermal voltage converter, according to ASA Standards, is
a thermocouple 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
collectors can be used to make highly
accurate voltage measurements at audio
and ultrasonic frequencies. The
frequency range of such voltage converters
is limited primarily by the residual
nonlinearities of their wire-wound resistors,
but tests have indicated that for some of
them good performance might be expected
at frequencies approaching 1 mc.

This paper describes thermal voltage
converters of low and computable
nonlinearities 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 detector
carbon resistors have been construc-
ted 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 50 mc. These rms voltage
converters may also be used to calibrate
12-1 (audio-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, 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 thermocouple
that was obtained with the alternating
voltage. The converters are calibrated
by the usual methods used for
thermocouple voltmeters.

The paper concludes by discussing
the advantages and disadvantages
of thermal voltage converters
compared to other types of
converters, and by presenting
some typical applications.


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The authors wish to acknowledge the help of R. Richardson and J. Solod, who checked the equations and carried out the computations which made possible Fig. 4 and the last column of Table II, and of R. Hill, who assited with some of the measurements. Thanks are also extended to M. C. Delit and L. Redlich for their careful calibration of the 1-volt converter.
first soldering the resistor, \( R \), to the thermocouple, \( TE \), and to the coaxial input connector, \( A \), which is mounted in disk, \( D_a \). This disk is then fastened to the cylinder, \( F \), and the two thermocouple leads are soldered to the 2-pin output connector, \( B \). Disk \( D_b \), 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 thermocouple 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.

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 \( S_1 \) is connected to \( F \) by a manganin strip, and is fastened to \( F \) by three equally spaced screws. Slots in \( F \) make axial adjustment of \( S_2 \) possible. The end-plate of \( S_2 \) is secured 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 errors above 10 nC when used in earlier converters. The 5- and 10-ma uhf thermocouples, 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.

A Lindeck potentiometer rather than a millivoltmeter is connected to the output end of the unit 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 500 mm (millimeter)/\( \mu \)a (microampere) it provides a selected resolution of either 2 or 10 \( \mu \)v (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 \( \mu \)v) and its freedom from drift (much less than 0.01% per minute under ordinary laboratory conditions).

**Theory**

Because of the geometry, the resistor, \( R \), in the cylinder or each low-voltage converter (without inner shields) may be represented as a transmission line of length, \( L \), with a uniformly distributed series impedance of \( \rho R \) ohms per unit length and a uniformly distributed shunt admittance, \( \rho Y \) millihms per unit length.
resistance of $y$ miles per unit length. The line is terminated by the heater of the thermocouple. We are interested in the magnitude of the transimpedance $V_x = V_I$, where $V_I$ is the input voltage being measured and $I$ is the current through the heater. If the heater resistance, $R_h$, is much less than that of the resistor, $R$, we may in 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 resistance on $V_z$. Then by ordinary steady-state transmission-line theory,

$$Z_x = \frac{Z}{\sqrt{2Y}} \sinh \sqrt{2Y} \quad (1)$$

where $Z = \alpha CR + j\omega L$, and $Y = \gamma j\omega C$ and $R$, and $Z_x$ and $C_x$ 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 reacances are small.

We may define the parameters $a = \alpha CR$ 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

$$Z_x = \frac{Z}{\sqrt{2Y}} \left(1 + \frac{Z}{a} + \frac{Z^2}{a^2} + \ldots\right)$$

Then if all terms in $a^2 Z^2$ for which $m > n > 0$ are discarded we find that

$$Z_x = R(1 + B) \left[1 - \frac{a^2}{6} - \frac{a^4}{120} + \ldots\right]$$

and, to the same order,

$$Z_x \approx R \left[1 + \frac{a^2}{180} - \frac{a^4}{29} + \ldots\right]$$

(2)

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

$$S = \frac{V_x - V_{dc}}{V_x} \quad (3)$$

where $V_x$ and $V_{dc}$ are the true alternating and direct voltages required to obtain the same response (output emf) of the converter. If the thermocouple has an a-c-d-c difference and we define $b = h/a$, this becomes

$$S = \frac{|Z_x| - R}{R(1 + h/a)} \quad (4)$$

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

The relation makes it possible to estimate $S$ to this approximation very simply. For the cylindrical construction of Fig. 1 with a cylindrical unspirated resistor, $L = 0.012\text{cm}$ microhenry and $C = 0.61\text{cm}$ microfarad, where $M = \log_{10}(g/h)$ and $g$ and $h$ are the diameters of the cylinder and resistor, respectively, and $a$ is in centimeters. Thus numerically,

$$b = 3.8 \times 10^{-15} \text{ m} \text{ cm}$$

and $S = 0.09 \text{ cm}$. Then $S = R \text{ cm} \text{ m}$. $A = m^2 + 2m + 1/3$ and $B = m^2 + 2m + 5/15$.

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

<table>
<thead>
<tr>
<th>Voltage Range</th>
<th>Converter A</th>
<th>Converter B</th>
<th>Applied Load</th>
<th>Comparative A-C-D-C Difference, $D$, Per Cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 mV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 mV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 mV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1 mV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.01 mV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: $D = 100(S_2 - S_1)$, where $S$ is defined by equation 3, and the subscripts refer to converters A and B.

Additional information see at 20 and 200 ohms.
The values of $S_0$ 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 $R_0 << R$, application of transmission line equations, with careful attention to signs, gives for the desired transimpedance,

$$Z_2 = \sqrt{\frac{Z_0}{Y_1}} \cos \sqrt{Z_0 Y_1} + \sqrt{\frac{Z_0}{Y_0}} \sinh \sqrt{Z_0 Y_2} \tag{7}$$

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

$$Z_2 = \frac{Z}{\sqrt{Y}} \ \sinh \sqrt{ZY}$$

Thus the transimpedance is twice that of either line, and the a-c-d-c difference, $S_0$, 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 $S_0 = 0$ when $Z_1/\sqrt{Y} = 1.032$, where $\xi$ and $\zeta$ 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 to 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 Pennybacker. 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 and 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 emf 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 self-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 $\mu$V, 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. 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 voltages. 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. 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 0.05% or less, and were less than 0.4% up to 30 mc. For 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

<table>
<thead>
<tr>
<th>Frequency, Mc</th>
<th>Applied Voltage, Volts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.992</td>
</tr>
<tr>
<td>10</td>
<td>0.998</td>
</tr>
<tr>
<td>30</td>
<td>0.999</td>
</tr>
<tr>
<td>100</td>
<td>0.999</td>
</tr>
<tr>
<td>300</td>
<td>0.967</td>
</tr>
<tr>
<td>600</td>
<td>0.952</td>
</tr>
<tr>
<td>900</td>
<td>0.943</td>
</tr>
<tr>
<td>1200</td>
<td>0.893</td>
</tr>
</tbody>
</table>

*For same reading of millivoltmeter at each frequency

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 1.3 times the usual length. At 40 mc the measured a-c-d-c difference was changed by less than 0.05% when the resistor was mounted 3/32 inch off the axis of the cyliner, 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% more than 30 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 unaninmity between converters having such a wide range of resisitors 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 0.05% at 40 mc and less than 0.1% below 30 mc.

Based on these considerations 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 0.005% to 10 mc and 0.1% to 90 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 1/3% 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 measured 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. 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 voltmeter, 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

<table>
<thead>
<tr>
<th>Rated Voltage, Volts</th>
<th>Per-Cent A-C-D-C Differences, 1095</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 mc</td>
</tr>
<tr>
<td>4</td>
<td>-0.3%</td>
</tr>
<tr>
<td>1</td>
<td>-0.5%</td>
</tr>
<tr>
<td>0.5</td>
<td>-0.5%</td>
</tr>
<tr>
<td>0.2</td>
<td>-0.5%</td>
</tr>
<tr>
<td>0.1</td>
<td>-0.5%</td>
</tr>
<tr>
<td>0.05</td>
<td>-0.5%</td>
</tr>
<tr>
<td>0.02</td>
<td>-0.5%</td>
</tr>
<tr>
<td>0.01</td>
<td>-0.5%</td>
</tr>
<tr>
<td>0.005</td>
<td>-0.5%</td>
</tr>
</tbody>
</table>

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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 n'th 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 \( L = \frac{1}{4\pi C} \), where \( R_0 \) and \( R_\infty \) 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. These 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 standard element, 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.

References


Discussion

Marley J. Loeb (Rowan Microstal 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 microcrystal core for adjustment. A wide frequency range and wide voltage range can be obtained on one instrument. However, the voltmeter cannot 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 may be necessary to calibrate the voltmeter at each voltage and frequency for which it will be used.

It should be pointed out that these meters are a problem, as they

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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.

P. L. Hermach and E. G. Williams: Mr. Leith'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 50±1%, where \( k = \pi C_0 \) and \( C \) and \( L \) 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.