have been adopted for overcoming this tendency which give promise of being successful but the fact remains that the weight of the armor is a great handicap: so much so that it rarely, if ever, has been possible to pick up conventional cable from depths exceeding 1,000 fathoms in fit condition to re-lay in deep water, even when it has suffered little or no deterioration from exposure to the sea water. That these defects are not caused by hydrostatic pressure is obvious because they can be duplicated readily by tests on shore under atmospheric pressure.

Not the least of the advantages of nonarmored cable lies in the almost complete elimination of torsional forces because of the close grouping of the helically shaped strength members about the neutral axis, and the fact that most of the elongation of the conductor which occurs upon the application of tension is achieved through distortion of the conductor helix, rather than through any reduction in cross-sectional area of the individual wire strands. (It is the stressing of soft copper beyond its low yield point in conventional cable which causes the knuckling tendency when the polyethylene pulls back strongly upon release of tension.)

No obstacle is seen to the design of nonarmored coaxial cable, but as this type usually is associated with submerged repeaters, reinforcement to provide enough strength to carry them to the bottom and raise them for servicing will be required for a reasonable distance on each side of each repeater, except possibly in the case of articulated repeaters of very light weight, and the economic advantage of the nonarmored design will depend upon the spacing of repeaters and their weight in sea water.

That this experiment has aroused so much interest is not too surprising. At a time when there are so many indications of a genuine resurgence of interest in ocean cables as the oldest and most dependable medium for international communications, anything which may affect their cost, their longevity and ease of repair at great depths is bound to be of real concern to those of us in the communications field who are aware of the spectacular advances which are now being made in transmission technique.

There is every reason to believe that this cable can be recovered and re-laid without impairment of its strength or coiling properties; and after a test of about 3 years (it has been in circuit almost 17 months now), assuming it still to be electrically sound, it is planned to do just that, utilizing the opportunity to examine every inch of it for evidence of teredo attack, chafe, and so forth, of course, and relocating it in another area where conditions are known to be none too good.

It is hoped that it will be possible to submit a further report at that time.

Accurate Radio-Frequency Microvoltages

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Synopsis: The questionable accuracy of radio-frequency microvoltages has been of great concern to the radio field for many years. There is an urgent need for a simple, yet reliable, source of microvolts for measurements in general and for radio receiver sensitivity determinations in particular. Extremely simple devices, which seem to satisfy that need most adequately, were recently developed. They are sources of potential drop obtained across a known resistance through which known currents flow. These devices provide constant voltage sources of accurate microvolts over a range of 1 to 10^5 and wider, at all frequencies to 300 megacycles and higher. They are adaptable for balanced as well as for unbalanced sources. Their electrical constants are simply determined by using known direct voltages and currents. Basic principles, design features, and applications are discussed.

THE RADIO and electronics field has been facing the problem of accuracy of radio-frequency (r-f) microvoltages since sensitivity of radio receivers came into prominence as a competitive index of performance. The reasons for the continued existence of this problem are too well known. There is no need to discuss them other than perhaps to indicate the major ones: namely, 1. the uncertainty in voltage source and load (receiver input) impedance values, 2. the uncertainty in performance of attenuators over wide frequency ranges and attenuations of up to 100 decibels and in many cases of higher values, and 3. the uncertainty in the accuracy and stability of devices monitoring the input voltages to the attenuators.

Considerable progress was apparently made as time went on, and a large section of the field has managed to attain high accuracies despite these difficulties. A recent poll of the field, instigated by the National Bureau of Standards in 1951 to determine the urgency of this problem, revealed the following status. Of about 70 standard voltage-generator manufacturing and applying laboratories (six of them in United Kingdom and France) about one-half believed they had available 1 microvolt at frequencies to 1,000 megacycles with an absolute accuracy of 30 per cent or better. The indicated accuracy was naturally better at lower frequencies. The other half was uncertain of their values in various degrees, in many cases exceeding 100 and in some 200 per cent. About one-half of them desired absolute accuracies of 0.5 to 6 per cent for all frequencies to 1,000 megacycles; the rest desired accuracies of 50 per cent or better.

The critical need of reliable tools to supply or measure microvolts accurately was therefore still very much in evidence. Devices apparently fulfilling this need most satisfactorily were recently developed. They seem to meet the most persistently demanded feature of a standard of microvolts, namely, extreme simplicity and reliability. These devices, referred to, for want of a better name, as "Micropotentiometers,"[1] are described later.

General Description of the Micropotentiometer

Basic Requirements and Principle Operation

In searching for a source of accurate and reliable r-f microvolts the following basic requirements seemed indispensable or highly desirable:

1. The output voltages of the source had to be known irrespective of loading conditions, that is, a constant voltage source was necessary.
2. Freedom from frequency corrections was essential at least over reasonable frequency ranges.
3. A reliable, simple, and rugged physical construction with a very minimum of component parts was most desirable.
4. The simplest and a very minimum of calibration requirements were essential.

All of these requirements seem to be satisfactorily achieved with the Micropotentiometer. In basic principle it is a source of potential drops obtained across a known resistance through which known currents flow. These resistances are of the order of *milliohms (for microvolt levels)*, and therefore constitute an essentially zero source impedance (constant voltage source) for all practical present-day needs. A cardinal requirement of

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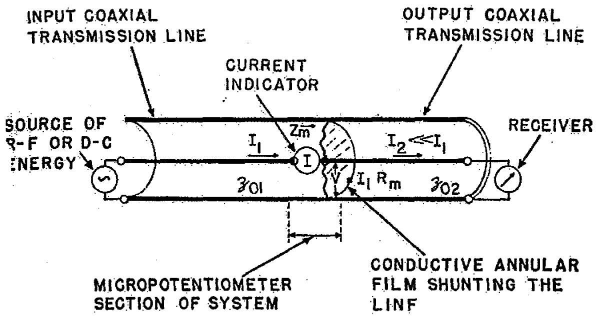
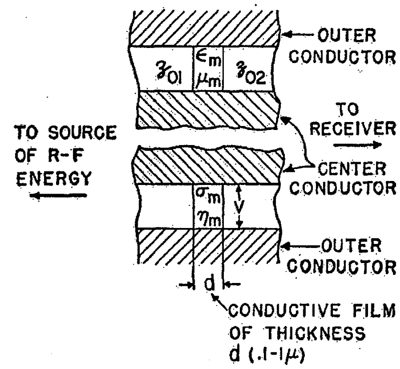


Figure 1 (left). Equivalent circuit diagram of system employing a Micropotentiometer

Figure 2 (right). Section of Micropotentiometer showing position of annular element in a low dielectric coaxial line



this impedance, as previously implied, was that its reactive component be negligible compared with its resistive component. This suggested the annular type of resistance element construction. The equivalent circuit of the Micropotentiometer together with the input and output circuits is that of a coaxial line shunted by a conductive film in a plane normal to the axis of the line, as shown in Figure 1. A source of r-f energy supplies current to the Micropotentiometer section of the system through a coaxial line and the voltage output V, from the Micropotentiometer, available across the annulus, is fed to the receiver either directly or through an output line. To a very good approximation the output voltage V is simply the product of the input line current entering the annulus and the d-c resistance of the annulus.

To show that this is true the transfer impedance of a thin conducting film placed as already indicated (see Figure 2) will be considered under the following assumptions:

1. The characteristic impedance of the coaxial lines is of practical magnitude, for example, any value between 20 and 200 ohms.
2. The bridging film has a finite high conductivity approaching that of silver, copper, platinum, and so forth. Perfect contact is assumed between the film and the coaxial conductors.
3. The diameter values of the coaxial lines are very small compared with a wave length.
4. The coaxial line terminating impedance (that is, the receiver input impedance) is of such a value that the impedances along the line, beyond the film, remain fairly high, that is, 1 ohm or higher.

The general field-theory approach[2,3] treats the solid metallic disk (or annulus) as a section of a coaxial line with an intrinsic impedance corresponding to that of the particular metallic medium. Under the preceding assumptions the fields in all the coaxial line sections are that of the dominant transverse electromagnetic (TEM) plane wave mode of propagation.

Let ϵ_m, μ_m, σ_m and η_m designate respectively the permittivity, permeability, conductivity, and intrinsic impedance of an infinite metallic medium. Under the preceding assumptions

$$\omega\epsilon_m \ll \sigma_m$$

where

$$\omega = 2\pi f$$

For copper at 1,000 megacycles

$$\omega\epsilon_m = 0.17 \quad \text{mhos per meter}$$

as against

$$\sigma_m = 5.7\times10^7 \quad \text{mhos per meter}$$

Therefore[3]

$$\eta_m \cong (1+j)\sqrt{\frac{\omega\mu_m}{2\sigma_m}} \tag{1}$$

The propagation constant in the same medium is

$$\gamma_m \cong (1+j)\sqrt{\frac{\omega\mu_m\sigma_m}{2}} \tag{2}$$

The characteristic impedance of a coaxial line with a solid conductor as a propagation medium is

$$Z_0 = \eta_m \frac{1}{2\pi}\ln\frac{r_1}{r_2} \cong (1+j)\frac{(\omega\mu_m)^{1/2}}{2\sigma_m}\frac{1}{2\pi}\ln\frac{r_1}{r_2} \tag{3}$$

where r_1 and r_2 are respectively the large and small radii of the conductors.

The d-c resistance of the annulus of thickness d is

$$R_m = \frac{1}{\sigma_m 2\pi d}\ln\frac{r_1}{r_2} \tag{4}$$

and the depth of penetration is

$$\delta = \left(\frac{1}{\sigma_m \pi f \mu_m}\right)^{1/2} \tag{5}$$

Therefore

$$Z_0 \cong (1+j)R_m\frac{d}{\delta} \tag{6}$$

and

$$\gamma_m = (1+j)\frac{1}{\delta} \tag{7}$$

Using well-known transmision line theory, the output voltage V of a line section equivalent to the annulus terminated by an impedance Z_r is given in terms of the input current I_1 by

$$V_r = \frac{I_1}{\frac{1}{Z_r}\cosh\gamma d + \frac{1}{Z_0}\sinh\gamma d} \tag{8}$$

and the transfer impedance is

$$Z_m = \frac{V_r}{I_1} = \frac{1}{\frac{1}{Z_r}\cosh\left[(1+j)\frac{d}{\delta}\right] + \frac{1}{R_m}\frac{\sinh[(1+j)d/\delta]}{(1+j)d/\delta}} \tag{9}$$

In this application $Z_r \gg R_m$, therefore for all practical purposes

$$Z_m = R_m(1+j)(d/\delta)\,\mathrm{csch}\,[(1+j)d/\delta] \tag{10}$$

or taking the first three terms of the expansion[4]

$$|Z_m| = R_m\left|1 - j\frac{d^2}{3\delta^2} - \frac{7}{90}\frac{d^4}{\delta^4} + \ldots\right| \tag{11}$$

The absolute value of the transfer impedance is therefore equal to the d-c resistance of the annulus to better than

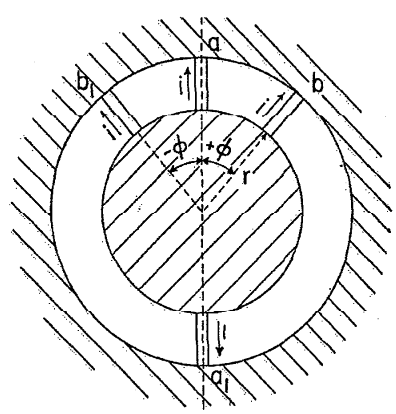


Figure 3. Radial conductor structure approaching that of a solid annular ring

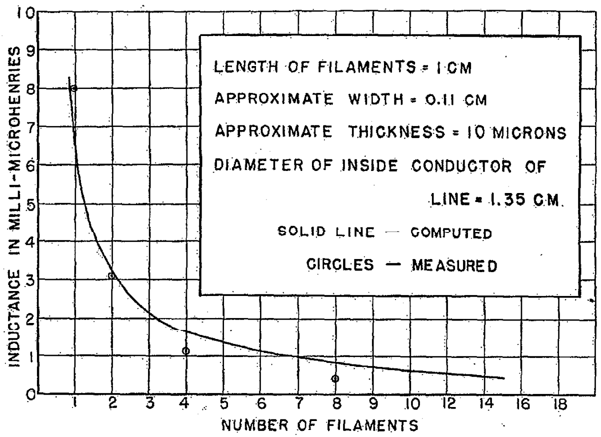


Figure 4 (left). Inductance of a system of tin (Sn) radial filaments short-circuiting the output end of a coaxial transmission line

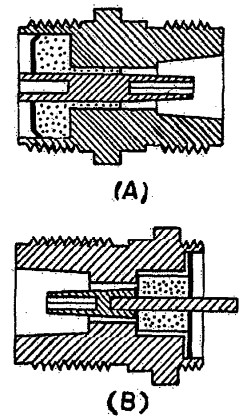


Figure 6 (right.) Cross sections of interchangeable Micropotentiometer resistance element assemblies. Solid black line indicates the metallic film, part of which is the annular resistor

A. Reversible unit using ceramic insulator. (When used with resistance film on the outside of the Micropotentiometer housing, maximum accuracy is assured. When reversed, type N connector is applicable)

B. Unit using glass bushing as insulator

1 per cent for $d/\delta \leq 0.5$, and

$$|V_r| = I_1|Z_m| \cong I_1 R_m \quad (12)$$

That this is true can also be shown in a simpler but less rigorous manner, as follows.

The input impedance Z_m' of the line section (Figure 1) having a metal as a dielectric and terminated in an open circuit or in an impedance $Z_r >> Z_0$ is

$$Z_m' \cong \frac{Z_0}{\text{tgh}\ \gamma_m d} = \frac{R_m(1+j)^{d/\delta}}{\text{tgh}\ [(1+j)^{d/\delta}]} \quad (13)$$

For sufficiently small values of d/δ therefore

$$Z_m' \cong R_m \quad (14)$$

Since for small values of d/δ the current in the annulus is uniform over its thickness to better than 1 per cent, the annulus can be treated as a resistance element is ordinarily treated at direct current, and the voltage drop across it is simply the product of its d-c resistance and I_1.

As was already mentioned, the success or failure of this device depended on the requirement of negligible reactance in the annulus. Therefore all possible substantiating evidence was investigated both analytically and experimentally.

In applying the lumped-circuit approach, the top limiting value of the inductance of an annular conductor carrying radial currents was derived as follows.

The annular ring can be looked upon as consisting of a large number of equal radial conductors of finite length and thickness, all connected in parallel. A square cross section may be chosen for these conductors and a maximum possible value of the ring inductance evaluated by computing the effective inductance of the system of radial conductors. Figure 3 shows four of these radial conductors starting at the periphery of the center conductor and ending at the outer conductor of a coaxial line. The coaxial conductors are at right angles to the radial elements and therefore have no mutual inductance with them. The return path for the current in the annulus is assumed far enough away to avoid any influence on the radial elements. Complete penetration of the current, that is, uniform current density in these elements is assumed at all frequencies. Consequently all deductions based on low-frequency analysis may be used at the higher frequencies at which current density remains essentially uniform.

Each radial element has self-inductance and mutual inductance with all the other elements. Assuming an even number of elements, for each element b on one side of a given element a there is another element b_1 located at an angular symmetry which will cancel the mutual effect of b with a. Thus the effective inductance of a will be

$$L_a = L_a' + M_{ab} + M_{ac} + \ldots + M_{ab_1} + M_{ac_1} + \ldots + M_{aa_1} = L_a' + M_{aa_1} \quad (15)$$

where L_a^1 is the self-inductance of element a and M_{aa_1} is the mutual inductance between element a and a_1 located diametrically opposite a.

Let d be the thickness of the element, and r be the radius of the inner coaxial conductor. Then the total inductance of the annulus, L_A, will be equal to the inductance of all the elements in parallel, or it may be considerably less than this value because of the additional parallel elements not accounted for, which complete the solid annular ring. Thus

$$L_A \leq \frac{d}{2\pi r}(L_a' + M_{aa_1}) \quad (16)$$

The self-inductance of a square bar is[5]

$$L_a' = 0.002l\left[\log\frac{2l}{0.447d} - 1 + \frac{0.447d}{l}\right] \text{ microhenrys} \quad (17)$$

where d = thickness of the square bar in centimeters and l = its length in centimeters.

The mutual inductance between elements a and a_1 will have a negative sign, because they are connected in series bucking, and is given by[6]

$$M_{aa_1} = -0.002[(2l+2r)\log(2l+2r) + 2r \times \log 2r - 2(l+2r)\log(l+2r)] \text{ microhenrys} \quad (18)$$

Computations for a typical annular ring for resistances of the order of one milliohm, having

$l = 0.1$ centimeter
$d = 2.5 \times 10^{-4}$ centimeters
$r = 0.5$ centimeter, result in
$L_a \cong 0.45$ millimicrohenry
$M_{aa_1} \cong 8$ micromicrohenrys
$L_A \leq 0.035$ micromicrohenry

The series reactance of this inductance is about 22 microhms at 100 megacycles which seems entirely negligible even at considerably higher frequencies, it being in quadrature with the resistive component. The actual series inductive reactance may be much lower, as already indicated, and seems still less important as the annular resistance is increased. The validity of the lumped circuit approach was verified experimentally. Equations similar to 16, 17, and 18 were used to compute the inductances of

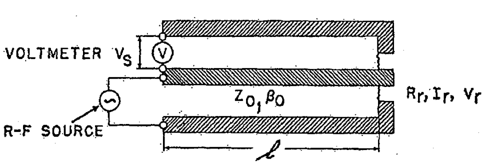


Figure 5. Schematic representation of "coaxial" type Micropotentiometer

symmetrical systems of radial tin (Sn) foil filaments of a centimeter in length and approximate width and thickness of 0.11 centimeter and 10 microns respectively, shorting the output end of a slotted measuring transmission line. The inductances were measured at 200 and 400 megacycles. Figure 4 shows a fairly good agreement between computed and measured values of inductances of these conductors, with a tendency of the measured values to diminish somewhat faster than the computed, with increasing number of filaments.

The only conclusive experimental evidence verifying the preceding analytical predictions was obtained by comparing voltage drops across annular elements with those of a voltage standardization bolometer bridge.[7] These results will be discussed later. Some further supporting evidence was found in the apparent failure to detect inductance in shorting disks of precision slotted transmission lines. None seemed to have been reported in the past anywhere in the field of slotted lines, resonance lines, nor in coaxial resonant cavities. However the impedance values here under consideration require a precision of measurement of voltage-node displacements of the order of a micron or better; such a precision was hardly available to anyone to date.

Ranges of Voltage and Frequency

The general conclusion that can be drawn from the preceding is that annular resistance elements of the type described can be used without frequency corrections over the entire ultrahigh-frequency range and higher, and indeed up to the frequency for which the metal-film thickness required is insufficient to maintain a homogeneous, continous metallic medium. This limit (about 0.05 of a micron) indicates that the top frequency of the Micropotentiometer application is dictated by the current indicators and higher nodes of propagation rather than by the resistance elements.

At any frequency the resistance of the annulus will remain the same as at direct current to within 1 per cent or better as long as the thickness of the conductive film does not exceed one-half the depth of penetration at that frequency for a thick conductor of the same material. If the film thickness is equal to the full depth of penetration, there may be an error of about 3 per cent in the r-f output voltage. It is necessary to select materials of proper conductivity and choose annular diameters of proper ratios and practical values to obtain various resistances desired to a given top frequency. One might call attention to the fact that the resistance is a function of diameter ratios and not of diameter values. Thus annular resistances of a fraction of a milliohm to 1 ohm and even higher may be used over very wide frequency ranges.

The voltage range of a given resistance element is clearly a function of the power it can dissipate in a particular physical arrangement. However, the power levels in question are generally of such a low level and the annular films are in such close proximity to large and efficient heat conductors that the voltage range of a Micropotentiometer with a given resistance element seems limited at the present time by the current monitoring elements rather than by power dissipation of the resistance films. No appreciable resistance changes were observed on 1- to 10-milliohm silver elements for currents up to an ampere.

Any means to indicate current accurately and independently of frequency are usable with the Micropotentiometers provided they can be physically located in such a manner that the same current is passing through the annular resistor as through the current monitor. This condition becomes more difficult to fulfill as frequency is increased. However, the fact that the annular resistances are very low renders the application of conventional r-f current indicators considerably less critical than in their application with high resistance elements. Thus thermoelements and thermistors were successfully used, as will be shown later, and other bolometer type and thermoelectric elements are applicable for frequencies approaching 1,000 megacycles and perhaps higher.

The low limit of the voltage range is controlled by the smallest practical diameter ratios of the annular elements, by the conductivity of the materials, by the accuracy with which low d-c resistance values can be determined as well as by the accuracy with which low current values can be measured. For frequencies up to the very-high-frequency range the low limit to date seemed of the order of 0.1 of a microvolt; for higher frequencies it was of the order of 1 microvolt.

General Design Features

In designing assemblies of components and housing of Micropotentiometers only one somewhat critical requirement has to be fulfilled. The resistance films comprising the annular elements and having various thicknesses down to a micron and lower have to be in perfect continuous contact with the outside and inside conductors and must remain mechanically rugged and stable. Other requirements are of the ordinary variety which can be readily met. One of these requirements concerns the proximity of the current monitoring element to the annulus and is not critical because there is a current loop at the annulus; the current falls off as a cosine function with distance towards the current monitor (or r-f power source). This feature tends to equalize the current distribution along heaters of thermoelements as well, and thus extends the frequency range. For example, a distance of 2 centimeters from the resistive film to the current indicator may cause a 1-per-cent error at 300 megacycles. With thermistors as current monitors this question seems of no consequence, even over the entire ultra-high-frequency range since thermistor beads having diameters of 15 mils can be placed right at the annulus.

Another noncritical requirement concerns the length of the output coaxial connector of the Micropotentiometers. This connector may be considered an integral part of the feeder supplying the standardizing voltage to a receiver or any other monitor. For best results the annular resistance film should be placed in the output plane of the Micropotentiometer and the connectors to the monitor and to the equipment being calibrated in terms of the Micropotentiometers should be mechanically matched. In case this cannot be done, then the annular resistance film should be placed as close as possible to the output plane. The accuracy will then depend on the length of the Micropotentiometer connectors and the input impedance to the monitoring feeder. To be more specific, the output of the Micropotentiometer may be affected in two ways. The first is the actual increase of the shunt admittance across the annulus; since the resistance of the latter is very low the probability of trouble from this cause is remote. The second is the transformation action of the short connector from the resistance film to the physical output plane which may contribute an error of several per cent in the ultrahigh-frequency range, depending on the monitor-feeder impedance. In the extreme case, if that impedance is infinite, there will be a cosinusoidal reduction of the voltage along the short connector as one travels from the output plane towards the annular film; for example, at 300 megacycles a connector 1.5 centimeters in length will have a voltage about 1 per cent higher at the output plane as compared with

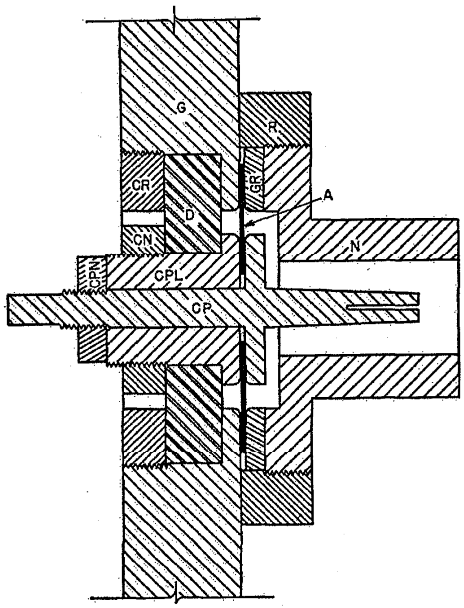


Figure 7 (left). Cross section of interchangeable Micropotentiometer resistance element assembly. Solid black line indicates resistance ring clamped between electrodes

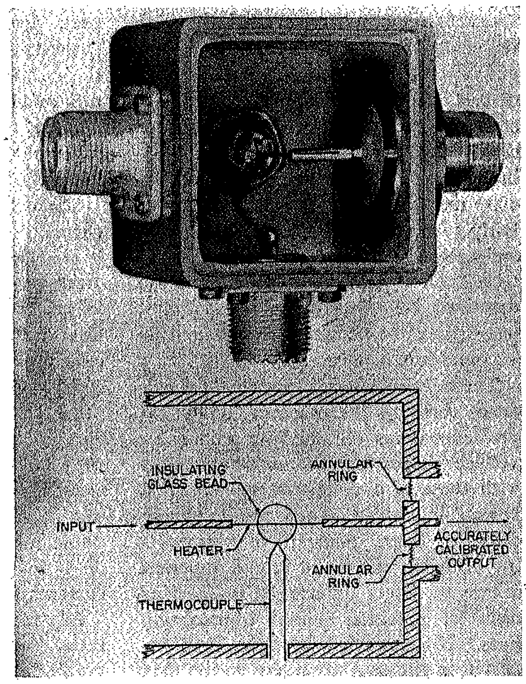


Figure 9 (right). Micropotentiometer employing a thermoelement as a current indicator

the standardizing voltage across the annulus. As the monitoring-feeder input impedance decreases, this error will be reduced and will be zero when this impedance is equal to the characteristic impedance of the connector.

One might point out here a practical advantage of these devices for universal standardization purposes. A known resistor of reliable r-f characteristics may be used as the coaxial center conductor of the output terminal. This would form a well-defined readily reproducible impedance of the source of standardizing r-f voltages when reliable voltage generators with given output impedances are required. Conventional standard "dummy antennas" may of course be used instead, with full certainty that the source impedance in this case is that of the dummy antenna only.

Types of Micropotentiometers

The basic principle of the Micropotentiometers lends itself to balanced circuit applications as well as to unbalanced. Since development work, so far, has been limited to unbalanced requirements, only the latter are discussed here.

The only other classification of these devices as to general type, aside from the preceding, is based on current measuring methods. These affect the basic physical structure of the units. All units using thermoelements may be essentially of the same construction and may have interchangeable annular and current indicating elements to cover a wider voltage range. Insulated-type thermoelements preferably should be used. In this type the structure requires only the thermocouple output terminals in addition to r-f input and output terminals. On the other hand, types employing bolometers (for example thermistors) or directly heated thermocouples require either r-f chokes or d-c blocking condensers, and in some cases, both.

One type, radically departing from the preceding and having some desirable features, is a Micropotentiometer using a reliable voltmeter instead of a current indicator. *Figure 5* shows this modification schematically. R-f power is fed into a section of an air or solid dielectric coaxial transmission line having negligible losses. A calibrated vacuum-tube voltmeter connected at the input to the line measures the input voltage. The output end of the line is terminated in a solid metallic disk containing an annulus of one-half the penetration thickness at the highest frequency of interest. Then, to a very good approximation

$$V_s = I_r Z_0 \sin \beta_0 l \qquad (19)$$

and

$$V_r - I_r R_r - V_s \frac{R_r}{Z_0} \csc \beta_0 l$$
$$= V_s K_1 \csc K_2 f \qquad (20)$$

where

R = the resistance of the annulus, ohms
V_r and V_s = the output and input voltages respectively, volts
I_r = the current in the short circuit, amperes
Z_0 = the characteristic impedance of the line, ohms
λ_0 = the wave length in the line, meters
$\beta_0 = 2\pi/\lambda_0$ = phase constant of the line
l = length of the line in meters
f = frequency in cycles per second

Since K_1 and K_2 are both constants

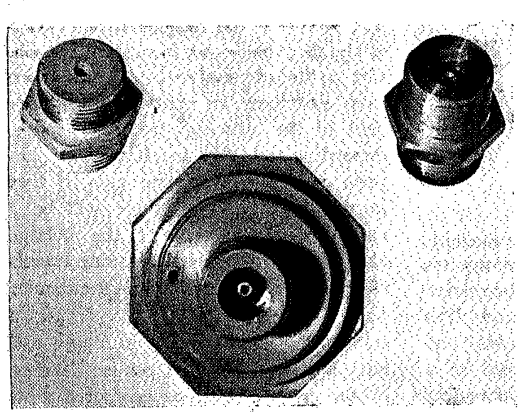


Figure 8. Micropotentiometer interchangeable resistance assemblies

A, B. Units using glass or ceramic bushings and evaporated and plated or fired-on films

C. Unit using clamped carbon disk

for a given air or solid dielectric line, one can compute and plot V_r versus frequency for $V_s=1$ volt to facilitate the determination of V_r over wide frequency and voltage ranges. A further simplification is obtained by using check frequencies for which the line length is an odd multiple of $\lambda_0/4$, in which case

$$V_r = \frac{R_r}{Z_0} V_s \qquad (21)$$

It can be shown that equation 21 holds for any value of R_r, thus a wide range of voltages is available at the output of this type of Micropotentiometer; for example, with $Z_0=50$ ohms, $V_s=0.1$ volt and interchangeable R_r elements of 0.5 to 100 milliohms, one can obtain V_r values of 1 to 200 microvolts.

Practical Micropotentiometers and Verification of Performance

The ideal Micropotentiometer should have a construction whereby the annular resistance element constitutes an integral part of the inner or outer surface of the relatively heavy metallic enclosure. There are numerous ways to approach this ideal and many of them were tried with various degrees of success. Details of construction and fabrication processes are beyond the scope of this discussion. However, three different satisfactory methods will be indicated on the basis of up-to-date experience. Low resistance elements, of the order of 0.2 to several hundred milliohms, were constructed in one of two ways. First, ceramic or glass cylinders were sealed as insulators between the two concentric conductors. For this sealing, metallic paints or pastes (silver, platinum, gold) were fired on the cylindrical surfaces of these insulators; the actual sealing was accomplished by soldering. An annular resistance element was then formed at one end of the coaxial assembly by evaporating and plating a given metal over its entire surface. Second, the same process was used as in the first case except that the metallic paints or pastes were also fired on one of the ends of the glass or ceramic insulators to form the annular resistor; evaporation and plating were thereby eliminated. A third method was applied successfully only to elements of the order of 1 ohms in resistance; carbon (deposited on bakelite) disks were clamped in a solid coaxial assembly; silver painted rings were used as conducting electrodes for the disk at the clamped surfaces. One modification of the low resistance elements made use of commercial Kovar-glass sealed terminals; metallic films fired on, or evaporated and plated over one side of the terminals formed the resistance elements; the terminals were then soldered into an appropriate housing. Figures 6, 7, and 8 show cross-sectional and photographic views of these elements and Figure 9 shows an assembled unit employing a thermoelement.

Once a Micropotentiometer is assembled, all that is necessary in order to determine its voltage output is to measure the d-c resistance of the annular film and to calibrate the current indicating element on direct current. However, in the up-to-date stages of this development, it was necessary to verify the results in terms of other independent methods at all frequencies. Reliability of new units can, of course, in the future be checked against older units with little difficulty. Agreement tests were conducted against the voltage standardizing bolometer bridge, mentioned previously[7] and precision wave guide below cutoff attenuators. These tests indicated agreement well within over-all experimental errors, that is ±1 per cent to about 50 megacycles and ±3 per cent to 300 megacycles. Measurements at higher frequencies have been conducted so far only on the clamped 1-ohm units and resulted in agreements of ±5 per cent to 900 megacycles.

Application of Micropotentiometers

Though the primary objective of these Micropotentiometers is to eradicate the wide uncertainty in the absolute values of voltages in the microvolt range, they can be used for numerous other purposes. The more obvious applications may be briefly indicated as follows:

1. Reference standard for accurate voltages in the range previously indicated for calibration of voltmeters, signal generators, field intensity meters, and so forth. The voltage and frequency range seems to be limited primarily by current-indicating facilities.

2. Sources of accurate voltages for direct use in place of conventional signal generators. The user has complete freedom to vary the internal impedance of these sources for various requirements with a high degree of certainty in the values of this impedance. A compact assembly incorporating an oscillator and Micropotentiometer may be constructed as a standard voltage (signal) generator.

3. Calibration of attenuators directly in terms of voltage ratios.

4. Determination of performance of current indicators, such as of various types of thermoelements.

5. Determination of output impedances of r-f sources. Resistance elements of the Micropotentiometers may be used to short-circuit the output of a source; the voltage output of these elements is then a measure of the short-circuited current of the source and consequently of its internal impedance.

6. Calibration of modulation meters. This application is common to all devices having an accurately known correlation between output and percent modulation, for example, the output of the couple of the thermoelement. Attention may be called here to the fact that presence of harmonics in the r-f carrier will normally have a negligible effect on the couple output, whereas the effect may be very appreciable on a vacuum-tube voltmeter usually employed with conventional voltage generators.

7. Applications where voltages in the microvolt range are desired without the usual Johnson noise of higher impedance sources present.

8. Applications where constant voltage sources are required, for example for Q-measurement circuitry.

9. Applications where a single device to cover the entire frequency range from zero to 300 megacycles and higher is essential.

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Discussion

Donald M. Hill (Boonton Radio Corporation, Boonton, N. J.): The micropotentiometer appears to be a worth-while contribution. Some time after the micropotentiometer was announced we had an application for it as the coupling impedance in a Q meter. After conferring with Mr. Selby concerning the methods of construction, we constructed a number of the resistors by firing a platinum-gold alloy on ceramic discs. These were tested over the frequency range from zero to 50 megacycles and found to be suitably free of inductance.

The temperature coefficient of the combination of an annular resistor and a thermocouple was found to be 0.11 per cent per degree centigrade.

One point which has perhaps not been sufficiently emphasized by Mr. Selby is that in order for the inductance to be negligibly low the resistive film must have complete axial symmetry. Until a manufacturing method can be devised which insures perfect symmetry, it will be necessary to test each resistor individually.

Myron C. Selby: The author wishes to thank Dr. Hill for his encouraging discussion. One can hardly question Dr. Hill's emphasis of the axial symmetry of the resistive film because it is a basic requirement of this development. Unfortunately we at the National Bureau of Standards have had no opportunity as yet to correlate degree of departure from symmetry with accuracy. Annular elements of superior symmetry were fabricated by means of evaporation and plating. However, there was no evidence to date that this fabrication resulted in units of higher average accuracy compared with others.

Load-Dropping Tests on a Large Ignitron Rectifier Installation

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A SERIES of load-dropping tests on ignitron rectifier circuits was conducted during March 1952 on an aluminum potline at the Mead (Wash.) Works of the Kaiser Aluminum and Chemical Corporation. The purpose of these tests was to obtain fundamental data on current and voltage surges encountered in a large ignitron rectifier installation when the potline load was tripped off by each of the following methods.

1. By a-c circuit-breaker operation.
   a. With auxiliary power maintained on the rectifier.
   b. With simultaneous tripping of auxiliary power.
   c. With simultaneous short-circuiting of all ignitor-firing circuits.
2. By automatic phase back to reduce the potline voltage to approach polarization value, followed by tripping of cathode circuit breakers.
3. By tripping all cathode breakers simultaneously.

Such fundamental data were desired in order to determine the best operating procedure to be used in dropping potline load in proposed higher capacity ignitron installations. In addition, it was desired to establish whether or not measures should be taken to protect existing installations against equipment failure from switching surges.

History

An outstanding development of World War II was the enormous increase in the use of rectifiers for the electrolytic reduction of light metals, both in this country and in Canada. During the war, a number of rectifier potlines operating at approximately 60,000 amperes and 650 volts were placed in service.[1] To meet the needs of the nation's defense, the use of ignitron rectifiers is again rapidly expanding both in total installed capacity and the relatively large number of units operating in parallel. Since the output of metal from the reduction process is almost directly proportional to the current through the pots, potlines which will carry 72,000 amperes at 750 volts are under construction, and lines are being proposed which will operate in excess of 100,000 amperes and 750 volts.

On rectifier installations placed in service during the war, potline loads are usually dropped by master trip of the cathode circuit breakers.[2] Some installations were originally set up to drop load by short-circuiting the ignitors to stop firing, but this method was abandoned because arc backs frequently accompanied the switching operation. On earlier installations, it was observed that dips of the order of 25 per cent in supply voltage caused the firing of the ignitrons to be erratic, resulting in unbalanced division of load between parallel rectifiers. Because of this phenomenon, little consideration was given to dropping load by opening the a-c circuit breaker. An advantage in master-tripping the cathode breakers was that auxiliary power supplying the firing circuits was invariably taken from the load side of the a-c circuit breaker, and it seemed to be desirable to keep the firing circuits energized when load was dropped. These factors led to the adoption of this method in spite of the stress placed on the cathode breakers, the last breaker to clear being required to interrupt approximately one-half of the potline current. In proposed higher capacity installations it would be desirable to relieve cathode breakers of this burden.

There have been a few rectifier transformer failures on installations made early in the war.[3] Some transformer failures were clearly the result of mechanical stresses, probably due to repeated arc backs, as evidenced by Figure 1 which shows mechanical distortion of the winding in the region of the failure. Magnetic forces resulting from short circuits or arc backs may have been responsible for dislodging the pressboard spacers between windings. Once the spacers between coils became dislodged, the high-voltage and low-voltage coils could shift with respect to each other, resulting in greatly increased magnetic forces which cause a part of the winding to collapse and burn out. As a result, replacement windings were constructed with additional bracing to withstand expected mechanical stresses resulting from arc-back currents, and subsequent windings were designed to withstand substantially higher mechanical forces.

Some failures, such as the one shown in Figure 2, do not show any mechanical distortion. This led to the consideration that these coils may have failed because of breakdown of the insulation by transient surges, although no other evidence of the existence of surges in such installations has ever been found. A possible source of excessive voltage surges is the rapid opening of circuit breakers either in normal switching operations or to clear faults. Another possibility is the phenomenon of arc starvation—the sudden interruption of current due to a deficiency of ions in the arc path. While it

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