THE GENERAL RADIO
EXPERIMENTER

# A BRIDGE TO TERAOHM TERRITORY

Thirty-one years is a long time for an instrument to be on the market. Imagine introducing an instrument now that will still be in a catalog dated 1995! Although the Type 544 Megohm Bridge has been modified occasionally, it is still basically the same instrument that it was in 1933,[1,2] and it is still a popular item. The longevity of this "circuit classic" may be some sort of record, and is a tribute to its design and its designer.

This instrument is a self-contained Wheatstone bridge system, which uses a vacuum-tube detector to achieve the sensitivity necessary for the measurement of high resistances. While there

[1] R. F. Field, "Bridge + Vacuum Tube = Megohm Meter," *General Radio Experimenter*, 8, 1 and 2, June–July 1933.

[2] R. F. Field, "The Megohm Bridge," *ibid.*, 12, 2, July 1937.

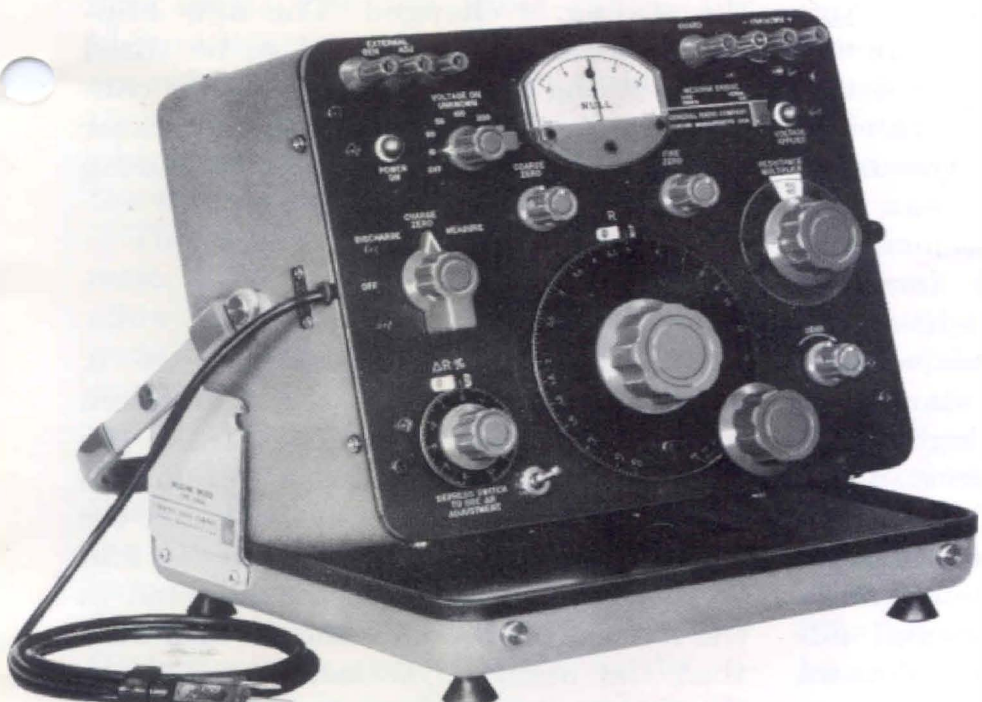

Figure 1. Panel view of the Type 1644-A Megohm Bridge. The Flip-Tilt case permits the panel to be positioned at any desired angle. Inset shows the older Type 544-B.

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hasn't been much change in the Wheatstone bridge in over a hundred years, except for improvements in the resistors used, there have certainly been advances in electronic circuits, which are used in the detector and voltage source.

In the new TYPE 1644-A Megohm Bridge (Figure 1) these advances have made practical these major improvements over the earlier TYPE 544:

1. Wider resistance range, extended three decades higher and two decades lower to give a total of 10 ranges, which cover $10^3$ and $10^{15}$ ohms.

2. Better accuracy; now 1% to $10^{12}$, 2% to $10^{13}$, and 10% to $10^{14}$ ohms. To get this accuracy at high resistances would have been difficult with the single-tube detector of the older instrument.

3. Seven internal test voltages, 10 volts to 1000 volts in 1-2-5 steps. Any other voltage in this range can be obtained with just one external resistor. Measurements at these lower test voltages are made possible by the more sensitive detector.

4. A $\Delta$R% dial for measurements of differences as small as 0.1%, for voltage- and temperature-coefficient investigations, and for precise comparisons against external resistance standards. These uses also require the high sensitivity of the new detector circuit.

5. A 100:1 minimum ratio between the ratio-arm resistor and the unknown as compared with 10:1 in the older instrument. This results in several advantages: The voltage on the unknown changes by only 1% over the dial range instead of by 10%; the ratio-arm resistor has a maximum of only 10 volts applied, so that its change with voltage is negligible; a lower-resistance ratio arm can be used on any given range, which, in several cases, permits use of a more stable resistor; and the lower resistance results in a shorter time constant when capacitor leakage resistance is measured. This extra factor of 10 in "bridge ratio" results in a 10-to-1 loss in bridge sensitivity, but is more than made up for by the improved detector.

6. A new internal self-calibration circuit permits checking of the resistance of the wire-wound and metal-film ratio-arm resistors and adjustment of the carbon-film types used on the three highest ranges.

As is apparent from the photographs, the styling is changed. The new Flip-Tilt case allows the panel to be tilted at any angle for the maximum convenience and comfort of the operator and provides a protective cover during transportation or storage.

## CIRCUITS

### The Bridge

The basic bridge circuit, Figure 2, is familiar to anyone who has taken freshman physics. It differs from the simple Wheatstone bridge circuit in two ways: T-networks are used in the ratio arm, $R_S$, on the top ranges, and a $\Delta$R% adjustment can be inserted in the fixed arm, $R_P$. One should also note that the main adjustment arm $R_N$ is the arm opposite the unknown, so that

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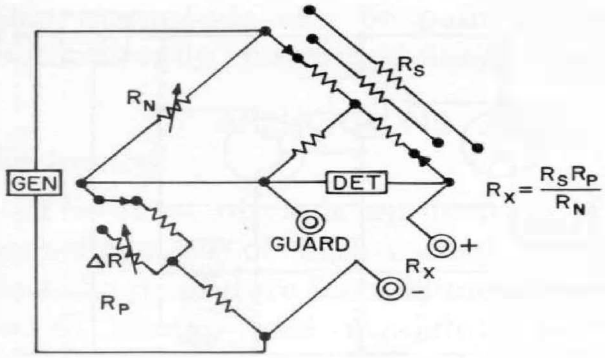



**Figure 2. Basic bridge circuit.**

its value is inversely proportional to the resistance measured. As a result, the R dial extends to infinity as $R_N$ goes to zero.

Ten ratio-arm resistors are used to obtain the ten resistance ranges. The five lowest-valued resistors are wire-wound and the next two are ¼% metal-film units. The top three ranges use high-resistance carbon-film types, which are neither so precise nor so stable and, therefore, have trimming adjustments, which can be set precisely by means of the internal self-calibration circuit.

The T-networks that make up the ratio arms on the two highest ranges allow the use of relatively low-valued resistors to obtain very high effective resistance. For those who have forgotten the Y-Δ transformation, Figure 3 will indicate how this is accomplished. If $R_1$ and $R_3$ are large and $R_2$ is small, the equivalent value of $R_Y$ can be very large. The other resistances of the equivalent Δ network fall across either the adjustable arm, $R_N$, where the resulting error is negligible if values are properly chosen, or across the detector, which results only in a loss in sensitivity. One advantage of this network over single resistors is that the low-resistance units are more stable; their use also keeps the bridge output impedance reasonably low to reduce capacitance-pickup and time-constant effects.

The main R adjustment, $R_N$, is the familiar cam-adjusted, wire-wound rheostat used in all our 1% bridges. The winding mandrel of this unit is shaped to give a logarithmic dial scale over a 10:1 range for constant percentage accuracy.

The $R_P$ arm is fixed unless the ΔR% switch is pushed, in which case a rheostat is inserted to give a ± 5% adjustment for the measurement of small resistance differences. This switch has a spring return so that the rheostat cannot be unintentionally left in the circuit where it could cause an erroneous reading on the main dial.

The junction of the $R_N$ and $R_P$ arms is brought out to the front panel as a guard point for measuring three-terminal systems. This is particularly useful for measurements on very high resistances, where guarded shields are necessary to avoid both leakage across the unknown and capacitance-pickup effects. Resistance from the + UNKNOWN terminal to the GUARD terminal shunts the detector and causes no direct error although it will, if low enough, reduce the detector sensitivity. Resistance from the − UNKNOWN terminal to the GUARD terminal shunts $R_P$ and will cause an error if it is below 50 megohms, which is relatively low compared with the values measured on this bridge. The guard will always tolerate the leakage resistance of shielded wires or of

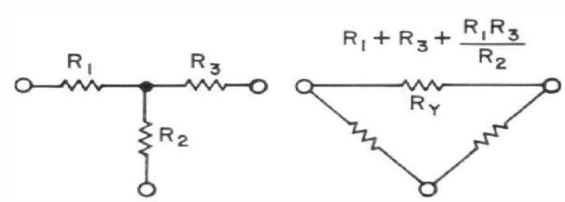
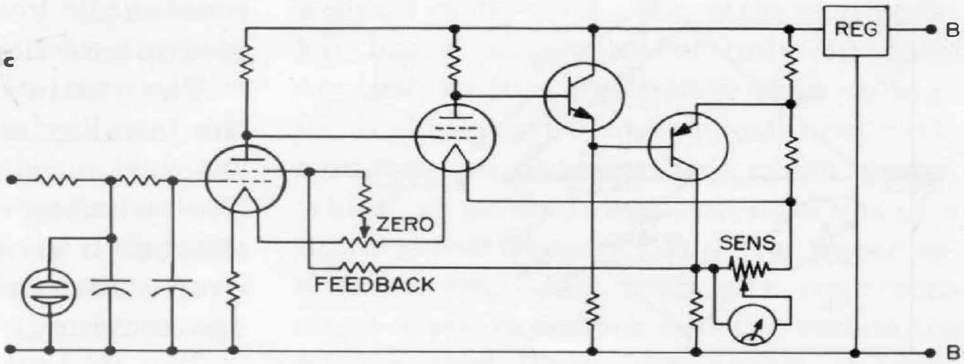



**Figure 3. Delta-wye transformation.**

Figure 4. Elementary schematic of the detector.




anything that can be legitimately called insulation.

## The Detector

The key to high-resistance measurements is high detector sensitivity and high detector input resistance. As noted above, other features can be traded for sensitivity but only if the sensitivity is adequate. The detector circuit used is shown (simplified) in Figure 4 for circuit enthusiasts. The input stage is a subminiature electrometer tube; this puts the input resistance up in the $10^{14}$-ohm range and keeps the grid current negligible. The subminiature tube that follows the electrometer reduces the impedance level so that two transistors can be used to complete the feedback loop. The feedback is returned to the screen grid of the electrometer, and the zero controls are also connected to this point.

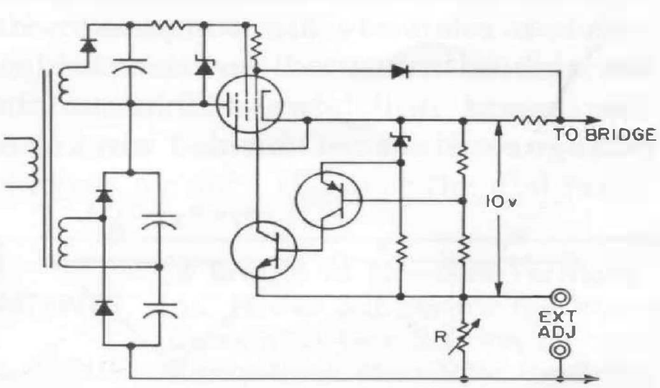



Figure 5. Schematic of the high-voltage supply.

The input tube is preceded by an RC filter to reduce the amplitude of ac signals, particularly hum, that might be picked up on the leads to the unknown resistance. A neon tube and the following 100-megohm resistor limit the grid current that could be drawn if high voltage were inadvertantly applied to the detector. The amplifier output drives a null-detector-type meter.

The sensitivity of the detector of the TYPE 1644 Megohm Bridge is over 200 times that of the TYPE 544. With well-aged tubes it can hold 100 microvolts for long periods, and voltage differences down to 10 microvolts can be detected with care.

## The High-Voltage Supply

While the high-voltage supply requires a vacuum tube as a series regulator, the use of transistors and Zener diodes makes practical the flexible circuit outlined in Figure 5. Here one resistor, *R*, controls the output voltage because the controlling bridge is balanced only for a given fixed current. This makes adjustment easy both internally and by external resistance.

This regulator has a typical regulation factor of 1000, can be shunted without damage, and is current-limited to approximately 8 milliamperes on the higher voltage ranges. A current of this magnitude can be painful, but is not generally considered dangerous.[3]

## APPLICATIONS

### Resistance

The most obvious application is the measurement of high-valued resistors, but the procedure for this measurement is so simple and straightforward it hardly requires mention. However, the use of the ΔR% dial for measurements of small differences in resistance is of interest to those making voltage or temperature-coefficient measurements. The bridge is close to ideal for the former because of its wide voltage range, detector sensitivity, and resolution of better than 0.1% on the ΔR% dial. Examples of ΔR% *vs* voltage for several resistors are shown in Figure 6. Temperature-coefficient measurements, of course, require a test chamber, and here the GUARD terminal is most

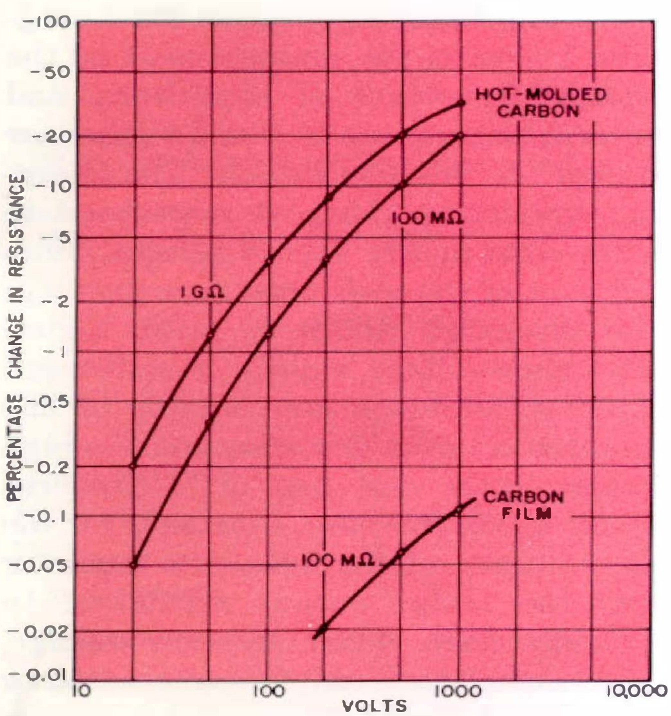
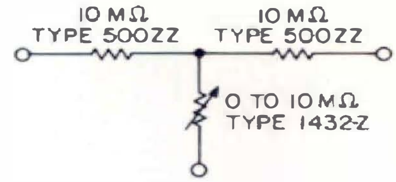



**Figure 6. Voltage-coefficient data as measured on the bridge for two types of carbon resistors.**

**Figure 7. Adjustable resistance standard covering a range of 100 megohms to one teraohm.**




useful to permit the use of shielded leads.

An interesting use of the ΔR% dial is in precision substitution measurements with external wire-wound standards. One may well ask where to find wire-wound standards in the gigaohm range. We make and sell two-terminal wire-wound resistors up to 10 megohms (TYPE 500-ZZ), and, with the aid of the Y—Δ transformation (Figure 3), one can easily make 0.1%, wire-wound, three-terminal resistances up to high teraohm ranges. A handy adjustable resistance standard, shown in Figure 7, covers the range from 100 megohms to 1 teraohm quite nicely. Unfortunately, there are limitations. The equivalent resistance to guard on one side shunts the $R_P$ arm of the bridge, effectively changing its value, but this error can easily be accounted for in the calibration relationship between the decade-box setting and the equivalent resistance. The other resistance to guard shunts the detector, causing a reduction in sensitivity at very high values of equivalent resistances. Thus, it takes 1000 volts applied for easy balance to 0.1%, when the T-network of Figure 7 is adjusted to give an equivalent 100 gigaohms.

### Insulation Measurements

The extended range of the new bridge is necessary for studies of many of the newer insulating materials. The guard

[3] Edwin Schecter, "Prevention of Electric Shock Hazard as a Basic Design Consideration," *Electrical Manufacturing*, January, 1960.

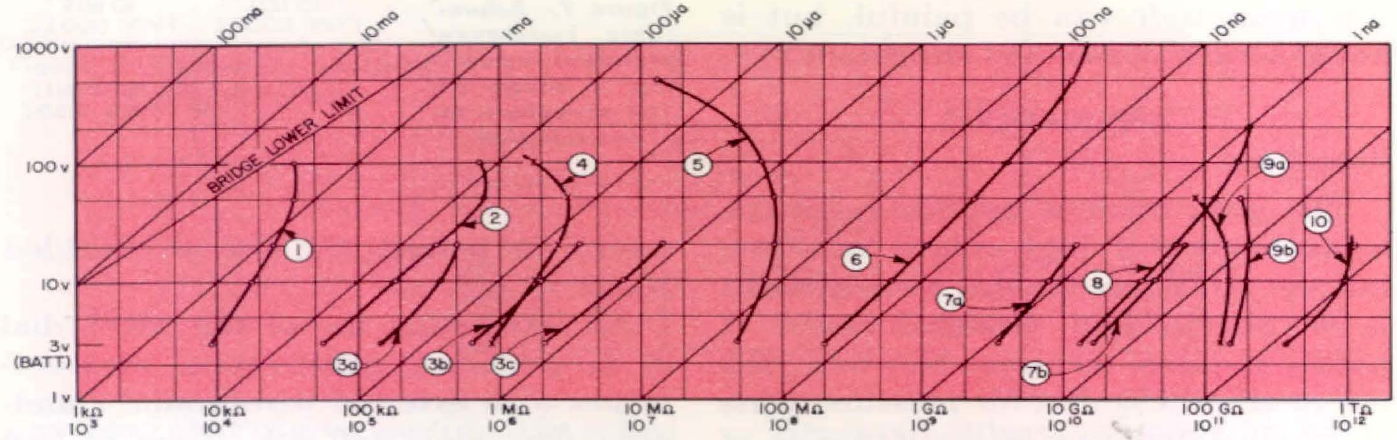



**Figure 8. Leakage resistance of several semiconductor devices as measured on the megohm bridge. Key:**

(1) 2N442 50-w Ge transistor (older type), $R_{CBO}$
(2) 2N1540 90-w Ge transistor, $R_{CBO}$
(3) 2N1304 Small Ge transistor, (a) $R_{CEO}$, (b) $R_{CES}$, (c) $R_{CBO}$
(4) 1N118 Ge diode, back resistance
(5) 1N3493 Si rectifier (200 v), back resistance
(6) 1N3256 Si rectifier (800 v), back resistance
(7) 2N2714 Si transistor, (a) $R_{CEO}$, (b) $R_{CBO}$
(8) 1N1298 Si diode, back resistance
(9) 2N2218 Si transistor, (a) $R_{CEO}$, (b) $R_{CBO}$
(10) 1N300 Si diode (selected), back resistance

is required for the standard ASTM electrode arrangements for both surface- and volume-resistivity measurements on insulation samples, and likewise it is often necessary to "guard out" alternate leakage paths in order to measure a particular piece of insulation in complex switch gear or machinery. The ability to make measurements with the unknown grounded as well as ungrounded finds application when measurements must be made to a grounded case or frame. The wider choice of voltages should permit measurements under conditions closely approximating those of normal operation, and the 1000-volt test voltage probably will find some use in hi-pot testing.

One should note that, while a bridge measurement in contrast to a megohmmeter measurement [4] requires a balancing adjustment, one can use the bridge for limit testing by setting the dial to the test limit and noting only the direction of the unbalance on the meter.

## Leakage Resistance Measurements on Capacitors

An important application for a megohm bridge is the measurement of the leakage resistance of capacitors, and several features are included in the new design for this application. The charging circuit can charge 1 microfarad to 1000 volts in less than a second, independent of the resistance range setting; the discharge circuit is much faster. The high-voltage supply is well regulated to minimize the coupling of line transients to the detector, and the high bridge ratio and use of T-networks result in shorter time constants for the combination of the unknown capacitor and the bridge output resistance. In extreme cases, when very-low-leakage, high-capacitance units are measured or when large dielectric absorption is present, this type of measurement becomes tedious to make with a bridge, but

[4] H. P. Hall, "Redesigned Megohmmeter Simplifies Insulation-Resistance Measurement," *General Radio Experimenter*, 37, 7, July 1963.

those who have made such measurements realize that it is tedious with any type of test circuit.

### Semiconductor Measurements

A relatively new application for a megohm bridge is in the measurement of the leakage characteristics of semiconductor devices. The lower test voltages of the new bridge permit measurement on transistors and diodes that would not tolerate the 100 volts supplied by the older bridge. Note that the range of the bridge easily covers the back resistance of low-leakage silicon types as well as germanium units whose resistance is many orders of magnitude lower (Figure 8). The measurement of these devices is straightforward and simple, but the interpretation of the shape of the curves is more subtle and is left to the reader. Note, however, that these devices have a positive voltage coefficient, while resistors have a negative one.

Figure 9. The Flip-Tilt case completely open (*right*) and closed for carrying (*left*).

### General

This new bridge with its many features is designed to meet present-day requirements for high-resistance measurement. Its range, accuracy, choice of test voltages, and ease of operation make it suitable for a wide range of applications in the design, production, test, and maintenance of electrical and electronic products.

— Henry P. Hall

## SPECIFICATIONS

**Resistance Range:** 1 kilohm to 1000 teraohms ($10^3$ to $10^{15}$ ohms) in ten decade ranges.

**Accuracy:** $10^3$ to $10^{10}$ ohms, ± 1%.
After self-calibration: $10^{10}$ to $10^{12}$ ohms, ± 1%; $10^{13}$, ± 2%.
$10^{14}$ ohms, ± 10%.
$10^{15}$ ohms, ± one scale division.

**Test Voltage:**

| | | | | | |
|---|---|---|---|---|---|
| *Fixed Voltages* | 10 | 20 | 50 | 100 | volts |
| *Minimum Resistance for Unknown* | 1 | 3 | 7 | 20 | kilohms |

| | | | | |
|---|---|---|---|---|
| *Fixed Voltages* | 200 | 500 | 1000 | volts |
| *Minimum Resistance for Unknown* | 50 | 150 | 500 | kilohms |

Voltage accuracy is ± 3% ± 0.5 volt.

**Short-Circuit Current:** <15 milliamperes at 10 to 50 volts; <10 milliamperes at 100 to 1000 volts.

**ΔR% Dial:** ± 5% range; accurate to ± 0.2% or, for small changes, to ± 0.1%.

**Minimum Test Voltage for 1% Resolution:** (for approximately 1-mm meter deflection).

| *Multiplier Setting* | *Max $R_x$* | *Volts* |
|---|---|---|
| 100 G or less | $10^{11}$ | 10 |
| 100 G | $10^{12}$ | 100 |
| 1 T | $10^{13}$ | 200 |

**Power Requirements:** 105 to 125 (or 210 to 250) volts, 50 to 60 cps, 13 watts.

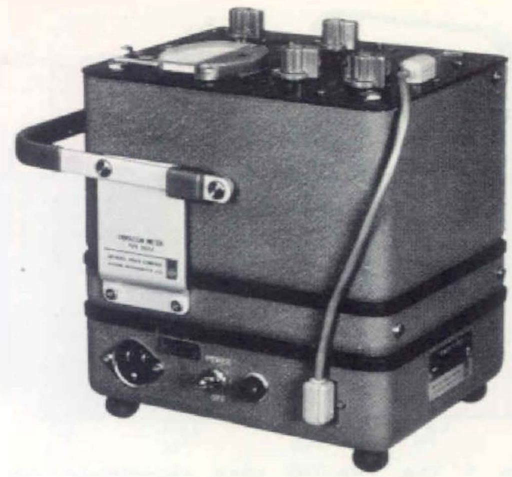
**Cabinet:** Flip-Tilt.

**Dimensions:** Width 12¾, height 12½, depth 7¾ inches (325 by 320 by 200 mm), over-all; with case closed and including handle.

**Net Weight:** 18 pounds (8.5 kg).

**Shipping Weight:** 22 pounds (10 kg).

| *Type* | | *Price* |
|---|---|---|
| **1644-A** | **Megohm Bridge** | **$625.00** |



## AC POWER SUPPLY FOR THE VIBRATION METER

The TYPES 1553-A and –AK Vibration Meters, which are normally battery operated, can be converted to power-line operation with the new TYPE 1262-C Power Supply.

This convenient ac power pack can be attached to the Flip-Tilt case of the vibration meter, as shown in the photograph. **Price: $135.00**

### SPECIFICATIONS

| Volts | Frequency cps | Watts | Filament Supply volts | Filament Supply ma | Plate Supply volts | Plate Supply ma | Dimensions | Net Weight | Shipping Weight |
|---|---|---|---|---|---|---|---|---|---|
| 105–125 | 50–400 | 3 | #1 1.3 | 31 | 4.5 | 61 | 7⅞ x 9⅛ x 3¼ inches (200 x 235 x 83 mm) | 2½ lb (1.2 kg) | 8 lb (3.7 kg) |
| 195–250 | 50 | 6 | #2 1.3 | 31 | 4.5 | 61 | | | |
| | | | #3 1.3 | 11 | 4.5 | 61 | | | |

## COAXIAL U-LINE SECTION

The U-Line Section is, as its name implies, a section of coaxial line in the shape of the letter U. It is supplied as an accessory with our TYPE 1607-A Transfer Function and Immittance Bridge, but is also a useful component in many coaxial line set-ups. In response to many requests, we are now making it generally available. **Price: $25.00**

## RELAY-RACK MOUNT FOR THE TONE-BURST GENERATOR

The TYPE 1396-A Tone-Burst Generator, described in the May, 1964, issue of the *Experimenter*, can be adapted for relay-rack mounting through the use of panel extensions, as shown in the accompanying photograph. Panel height is 5¼ inches.

Order TYPE 480-P308 Adaptor Plate Set. **Price: $7.00**

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**ERRATA — JUNE ISSUE**

The following errors have been noted in our June issue:

Page 11, line 11: $R_4$ should be $Q_4$.

Page 11, Figure 13: transistor should be labelled $Q_4$.

Pages 3 and 14: Figures 2 and 20 are transposed.



General Radio Company

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