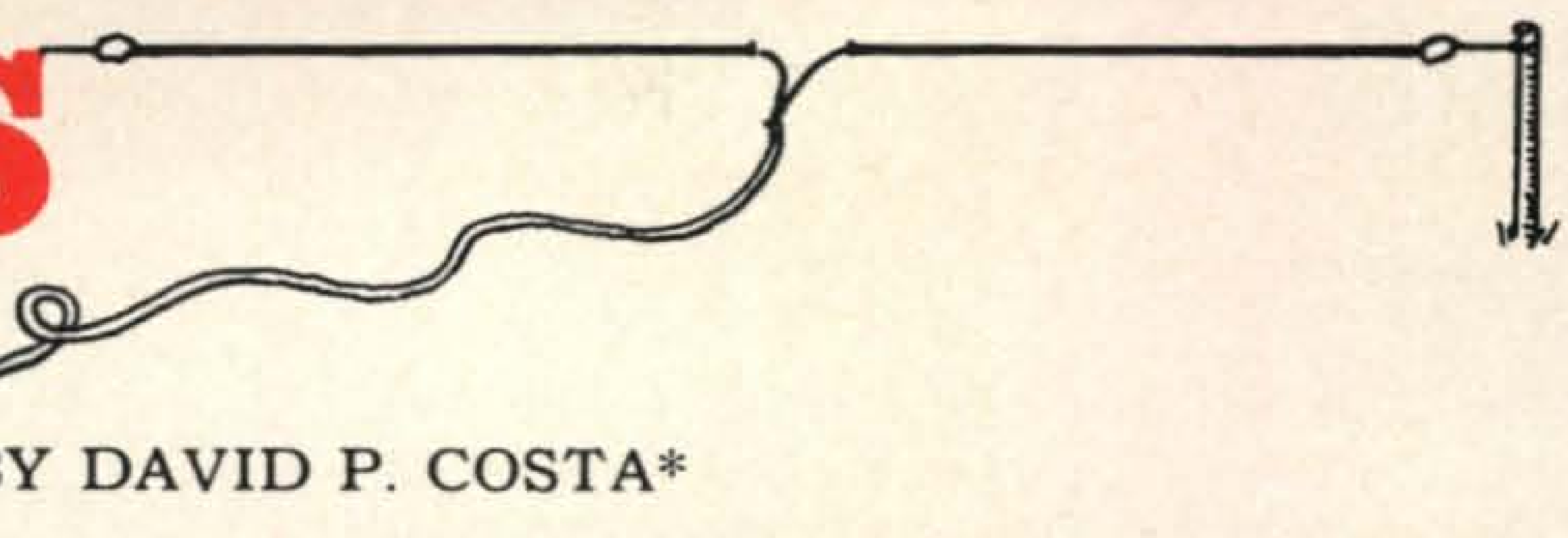
TRANSMISSION LINES



BY DAVID P. COSTA*

The author presents a review of the basic principles of transmission lines and then covers the characteristics, advantages and disadvantages of the various types.

A TRANSMISSION line is a device for guiding electrical energy from one point to another. How well this purpose is accomplished depends on the charactertistics of the transmission line used. The output end of an electrical circuit is coupled to the transmission line's input end, also called the generator end or source. The load is coupled to the output end, also called the load end or sink. The ratio of voltage to current at the input end is the input impedance. The ratio of voltage to current at the output end is the output impedance. If the line were of infinite length, the characteristic impedance would be the ratio of voltage to current on the infinite line. This value is constant for a given transmission line.

Distributed Constants

The transmission line is essentially a four terminal device. Two terminals are connected to the source and two terminals to the load. Between these terminals are distributed constants of inductance, capacitance, and resistance. Their values depend on the physical characteristics of the line such as the length, conductor sizes, spacing between conductors, and the dielectric (air or insulation) between the conductors.

If an infinitely long transmission line is assumed, then the characteristic impedance, Z_0, determines the current that flows when a given voltage is applied. The characteristic impedance is important in determining how well energy is transferred from the source to the load. For the infinitely long line, all of the energy is sent out on the line and none returns to the source. If a finite line is terminated with a resistive load equal to Z_0, the source appears to see an infinitely long line, and all the energy passes into the line. If the line is terminated in any other load, energy is reflected back to the source.

*Mechnical Engineer, Port of New York Authority, New York, N.Y.

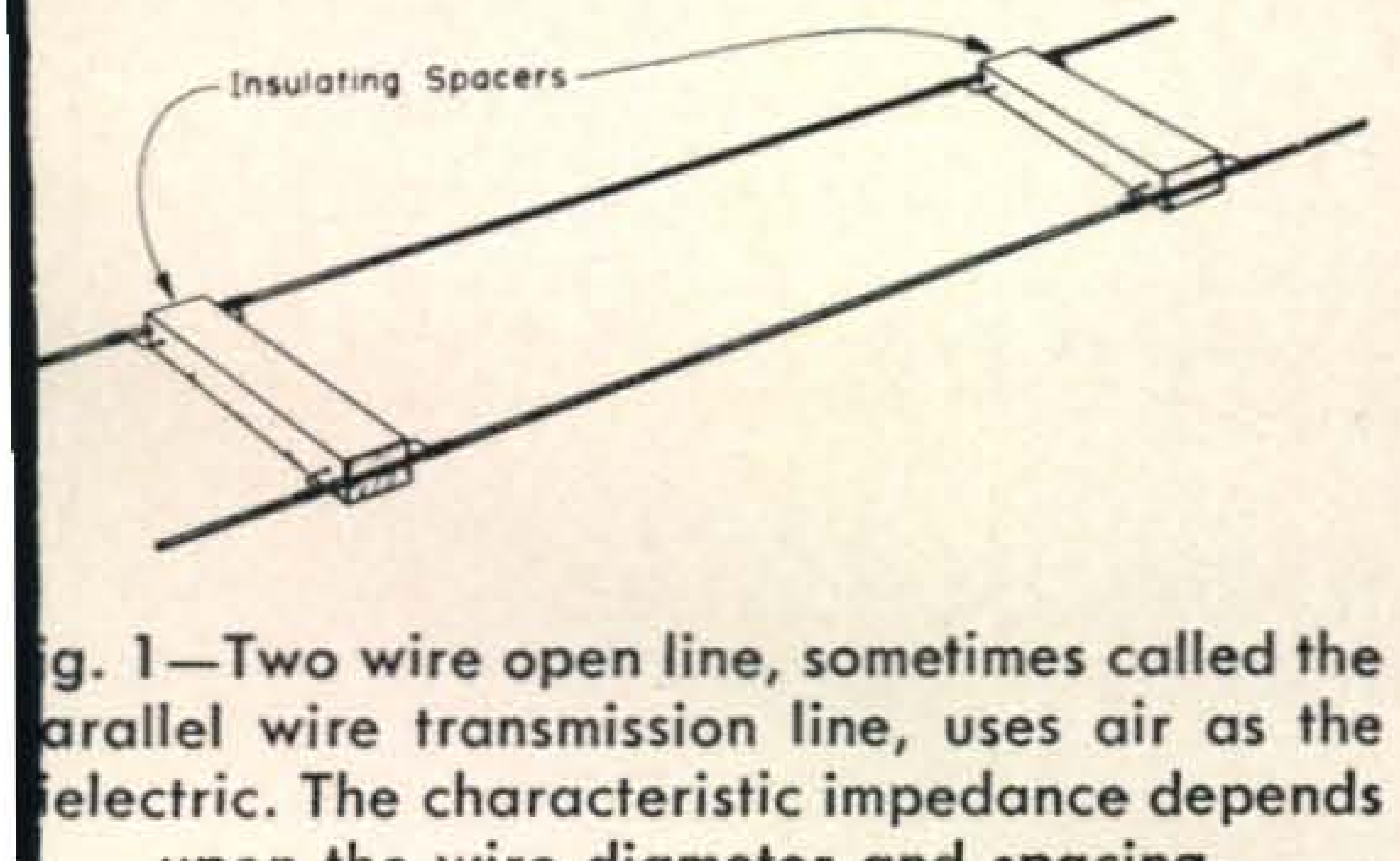


Fig. 1—Two wire open line, sometimes called the parallel wire transmission line, uses air as the dielectric. The characteristic impedance depends upon the wire diameter and spacing.

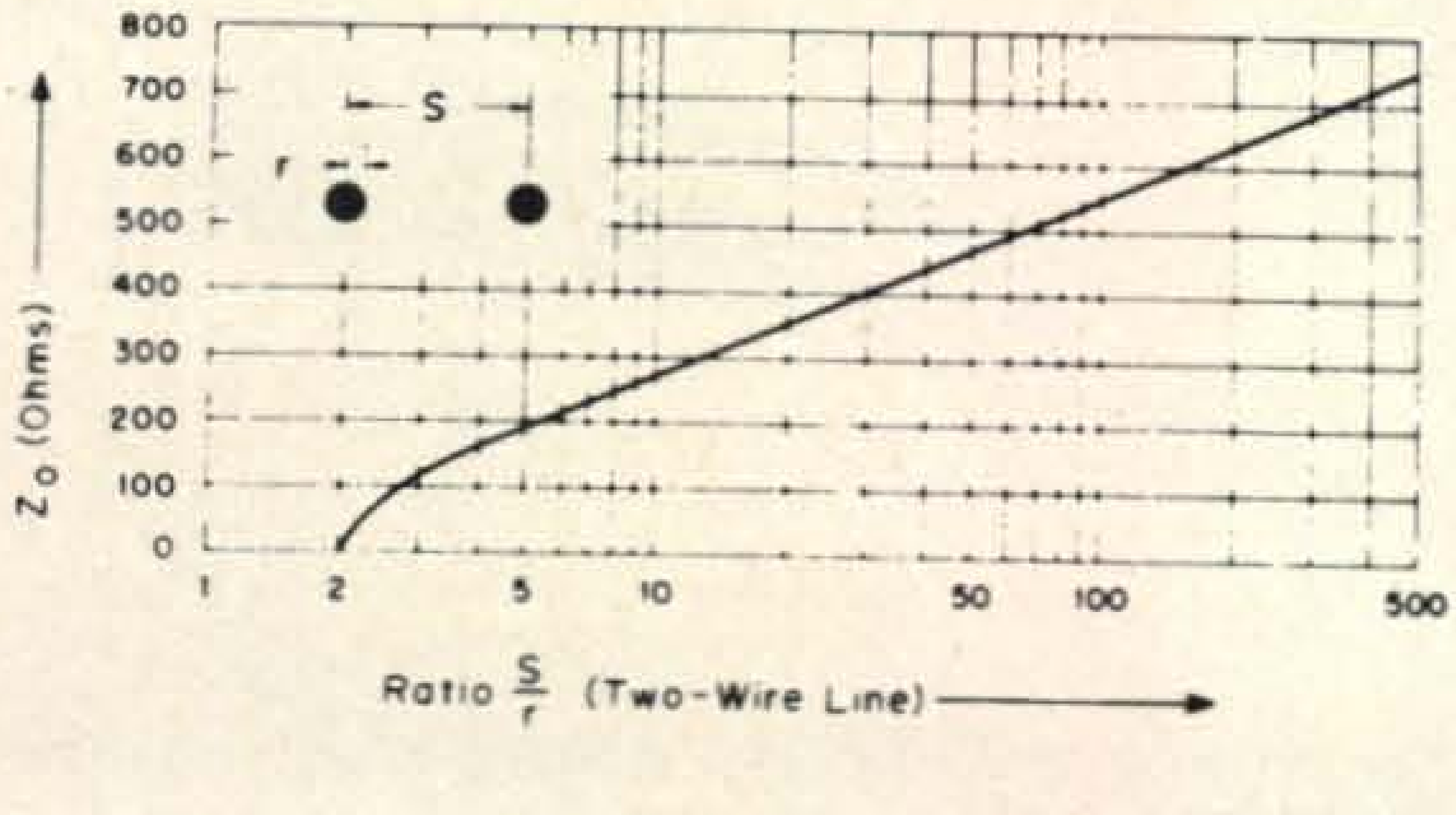


Fig. 2—A plot of the characteristic impedance, Z_0, versus the ratio s/r for a two wire open line.

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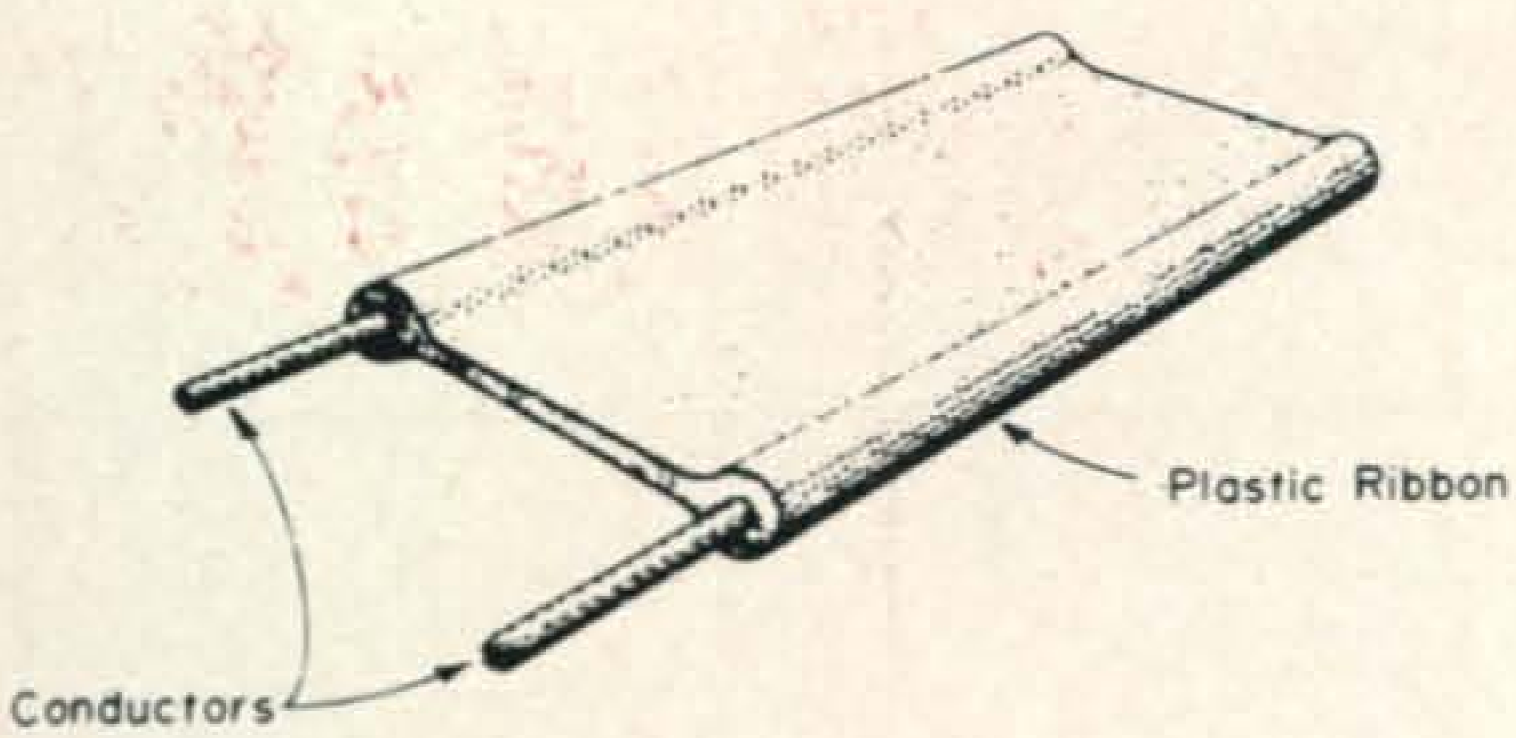

Fig. 3—Cross section view of an insulated two wire line. While more flexible and easier to run than the air dielectric type of fig. 1, insulated ribbon type shown has higher dielectric losses.

Attenuation and Losses

The ideal transmission line has no losses. It transfers all the energy available at the source to the load. Actual transmission lines, however, dissipate power in three ways; radiation, heating, and reflection.

Transmission lines of certain types tend to act like an antenna. Radiation losses of some of them can be considerable.

The resistance of the conductors dissipates a certain amount of power in the form of heat (I^2R loss). An I^2R loss also results from leakage between the conductors. Heat loss increases with lines having a lower characteristic impedance because of the higher currents that are permitted to flow.

A load with a value other than Z_0 reflects energy back along the line. This results in reflection loss. If energy is reflected, standing waves are formed, which means a changing ratio of voltage to current along the line, and therefore a changing line impedance.

If all energy is reflected from the output end and none is absorbed by the load, the impedance is purely reactive all along the line. If some energy is absorbed and some reflected, the impedance either can be resistive or can have both resistive and reactive components.

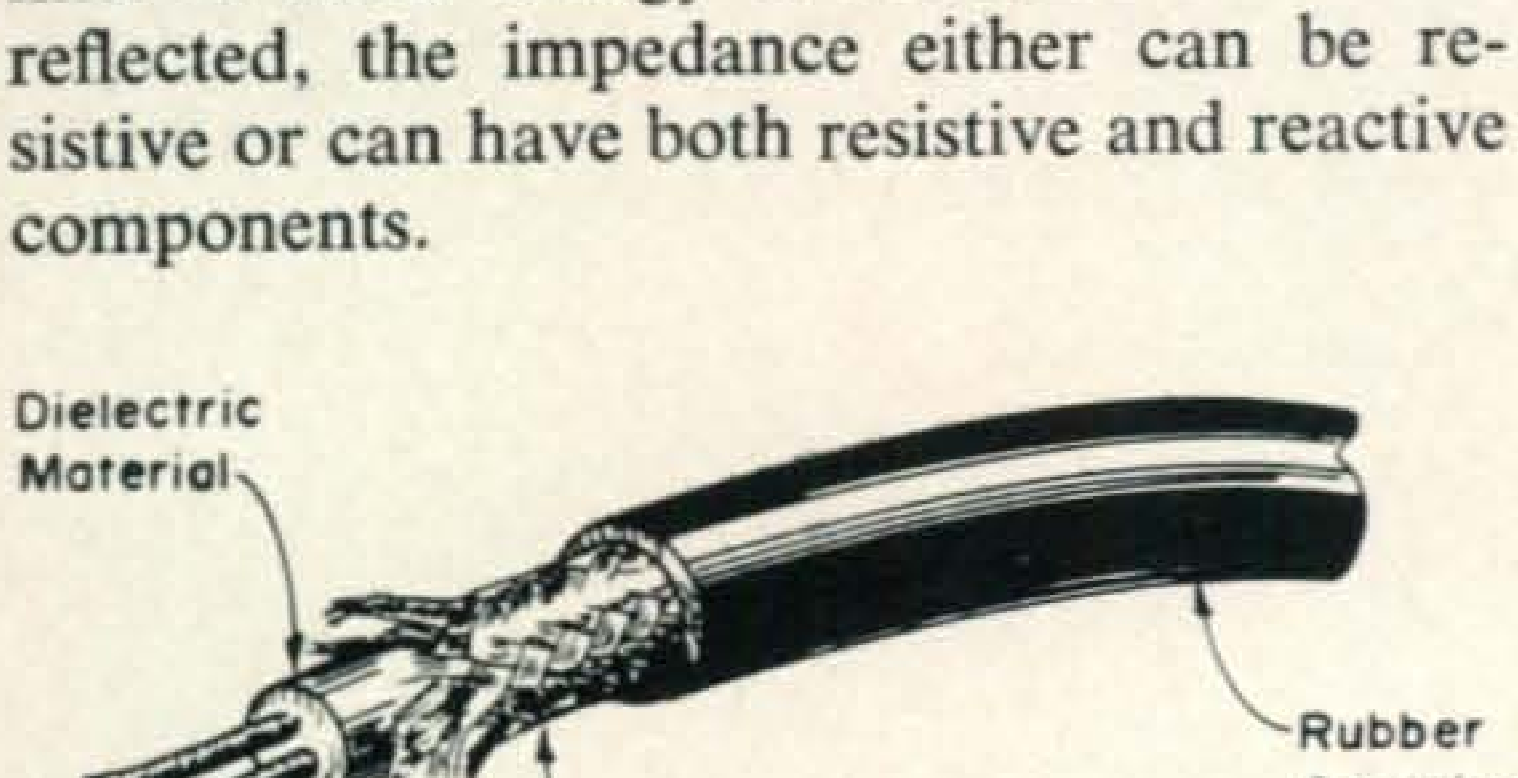

Fig. 4—The shielded pair shown above has the advantage of low radiation losses because the shield provides a uniform ground for both conductors.

When the source injects energy into a line impedance equal to the characteristic impedance, there are no standing waves and no reflections. Inductance, capacitance, and resistance found in a transmission line are distributed uniformly along its length. Therefore, no reflection of energy takes place unless the impedance at some point on the line is different from that caused by the distributed constants. The impedance seen by the source can be changed by changing the load. The travelling waves reaching the load suddenly encounter an impedance different from that along the line, resulting in the formation of standing waves and reflection of energy. Reflections occur as long as the load differs from Z_0.

Standing Wave Ratio (S.W.R.)

The actual loads connected to the transmission line usually have both resistive and reactive components. Considering the standing wave of voltage, the ratio of maximum to minimum voltage along the line is the standing wave ratio. The s.w.r. can be obtained by measuring the maximum and minimum current along the line. The standing wave ratio provides a measure of the energy reflected. When the line is terminated in a resistance equal to Z_0, the maximum and minimum values of current are the same. The s.w.r. is 1 to 1. In this condition, the load is said to be matched to the line. All of the energy is absorbed by the load (neglecting line losses), and there are no standing waves. Such a line is called flat, since the impedance, Z_0, is the same value all along the line.

If standing waves occur on the line with a given load, the s.w.r. is a measure of the degree of mismatch between load and line. For example, assume that a resistive load of 500 ohms is used to terminate a line with a characteristic impedance, Z_0, of 50 ohms. If the s.w.r. is measured, it is found to be 10:1. This is the same as dividing 500 by 50.

Impedance Matching

Assume that a transmission line has a characteristic impedance different than the load impedance. Since a mismatch occurs if the line is connected directly to the load, an intermediate element or impedance matching device must be used between the line and load.

Types of Transmission Lines

Transmission lines differ considerably in their construction and specific characteristics

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Various types are the single wire line, open two-wire line, insulated two-wire line, shielded pair, twisted pair, and coaxial lines.

Single Wire Line–This is the simplest type of transmission line where a single wire conductor links the source to the load. The return path completing the circuit is ground. The line is unbalanced; this condition leads to large radiation losses, which is a definite disadvantage. Another disadvantage is the lack of a constant physical relationship between wire and ground, which leads to a varying characteristic impedance, making the line difficult to match to the load. Because of these two disadvantages, the single-wire line is used rarely. It is found where its advantage of easy installation outweighs its disadvantages.

Open Two-Wire Line–Because it uses two parallel conductors, this is called also the parallel conductor line, or the open two wire line because the dielectric medium is air. The construction and installation of the open two wire line is nearly as simple as for the single-wire line. Although the balanced conductors act to reduce radiation loss, the balance is critical, and nearby metallic objects tend to unbalance the line and cause large radiation losses. The two wires used in this line are kept at a constant distance from each other by means of insulating spacers, or spreaders, shown in fig. 1. The actual distance used between the conductors depends on the impedance required, the diameter of the conductors, and the frequency of operation. The characteristic impedance of a two-wire line is relatively constant. For a two wire line having air as a dielectric medium, Z_0, is given by the formula:

$$Z_0 = 276\ log_{10}\ s/r$$

where s = space between conductor centers
r = radius of the conductors.

This formula is sufficiently accurate provided that the ratio s/r is 4 or greater. The graph of fig. 2 shows the variation in Z_0 produced by changing the ratio s/r. Currents flow through the two parallel conductors in opposite directions. If the two currents are 180° out of phase, the fields nearly cancel and the radiation loss approaches zero. At relatively low frequencies, this condition can be approached. As the frequency of operation is raised, however, the two currents tend to be more and more out of phase, causing considerable radiation loss. The loss can be reduced by moving the conductors closer together. Moving the conductors closer together lowers the characteristic impedance of the line. This can be seen from the equation above. In order to have a relatively high impedance and close spacing, it is necessary to reduce the conductor size. Reduction in size though, decreases the power capacities of the conductors. The higher the frequency of operation, the more difficult these problems become.

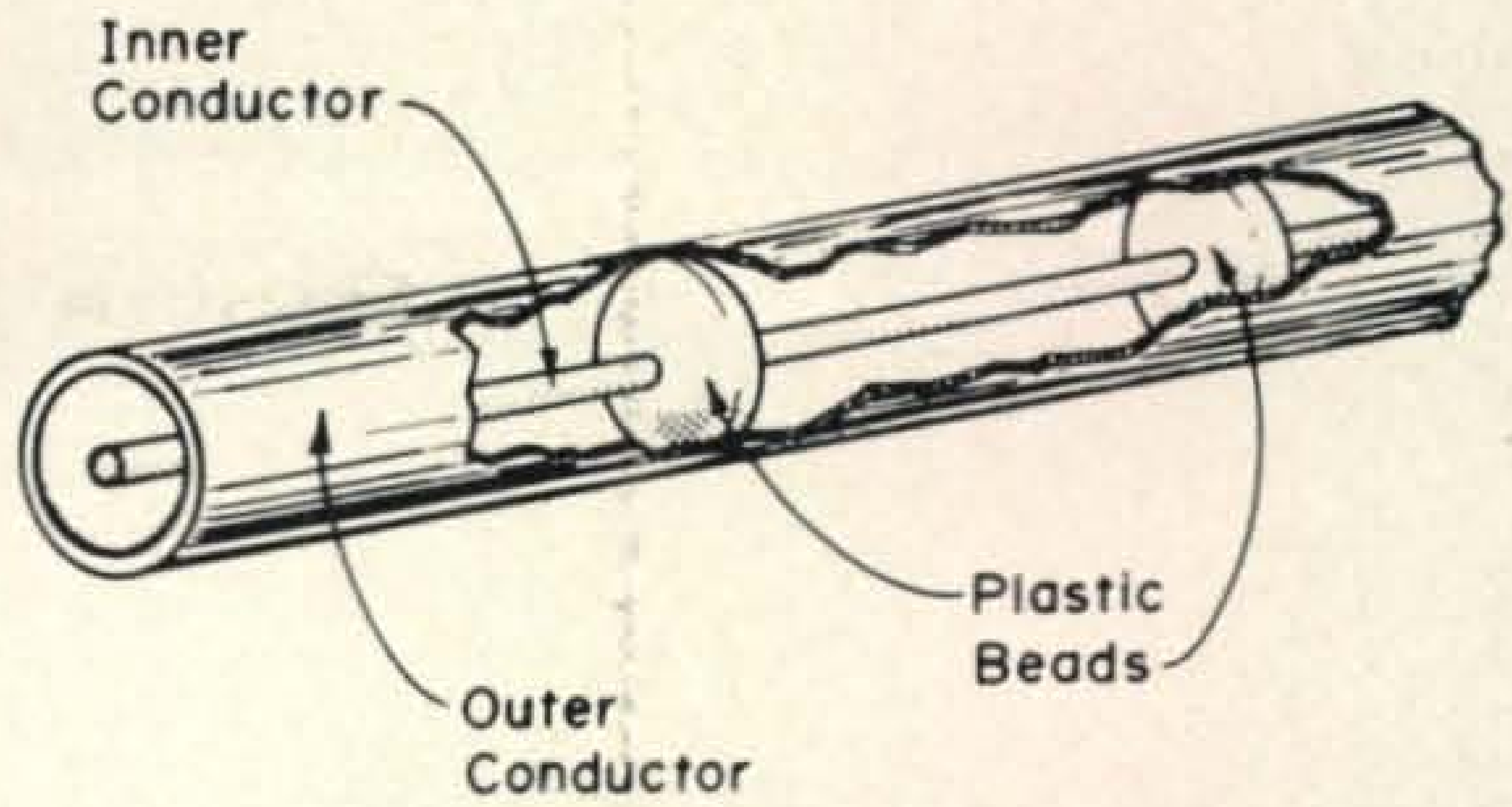

Fig. 5—A cut-away view of air dielectric coax using a flexible metal tube for the outside conductor. Coax is more often found in the form shown in fig. 4 but with a single inner conductor, a solid dielectric and braided copper outer conductor.

Insulated Two-Wire Line–Instead of having air as a dielectric medium, the two-wire line can be encased in a solid dielectric. This type of line has several advantages over the open line. Installation is simplified considerably because of its flexibility. For example, it is difficult to run the open wire line around a corner without changing the spacing be-

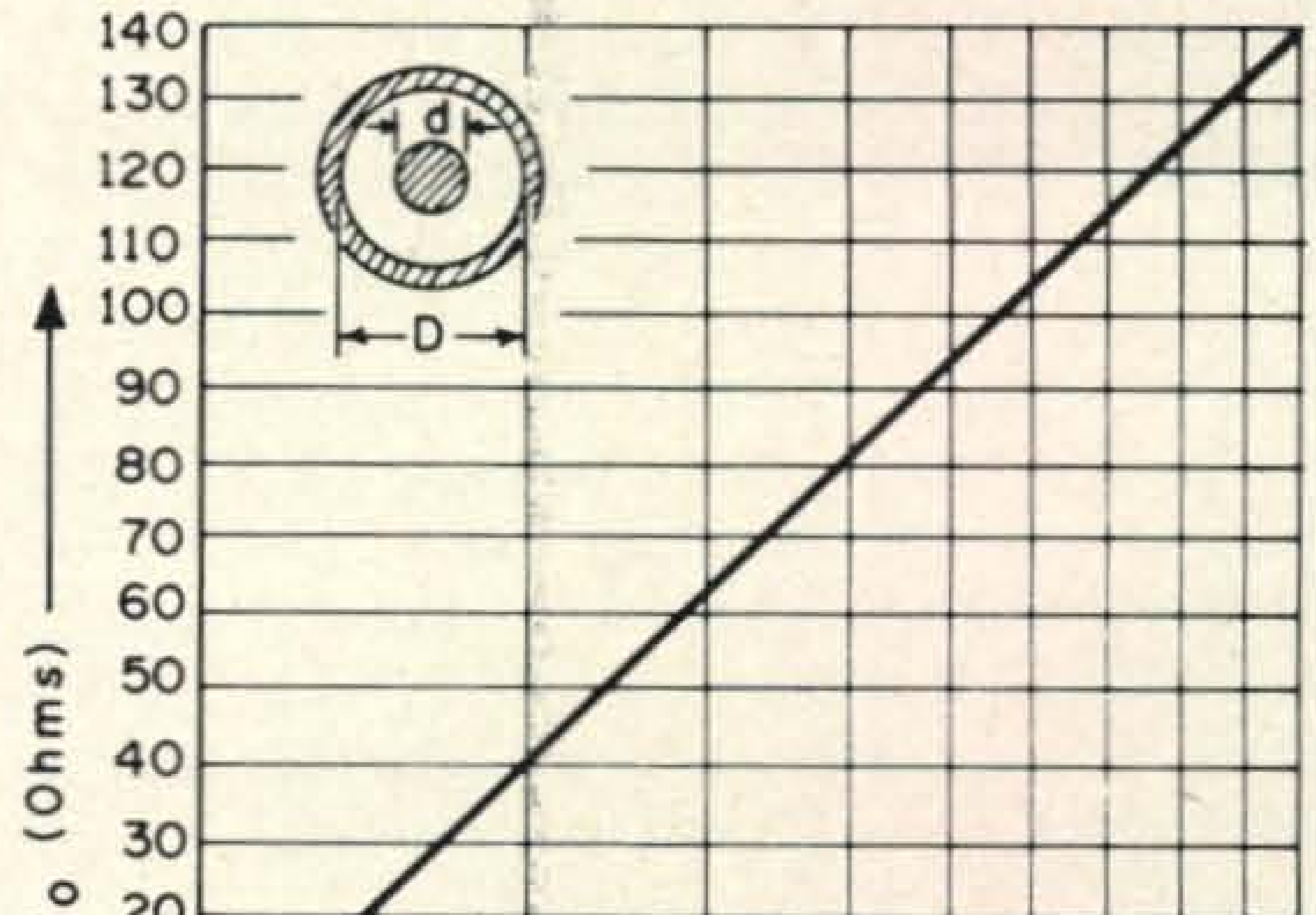

Fig. 6—Variations in Z_0 with changes in the ratio D/d for air coax.

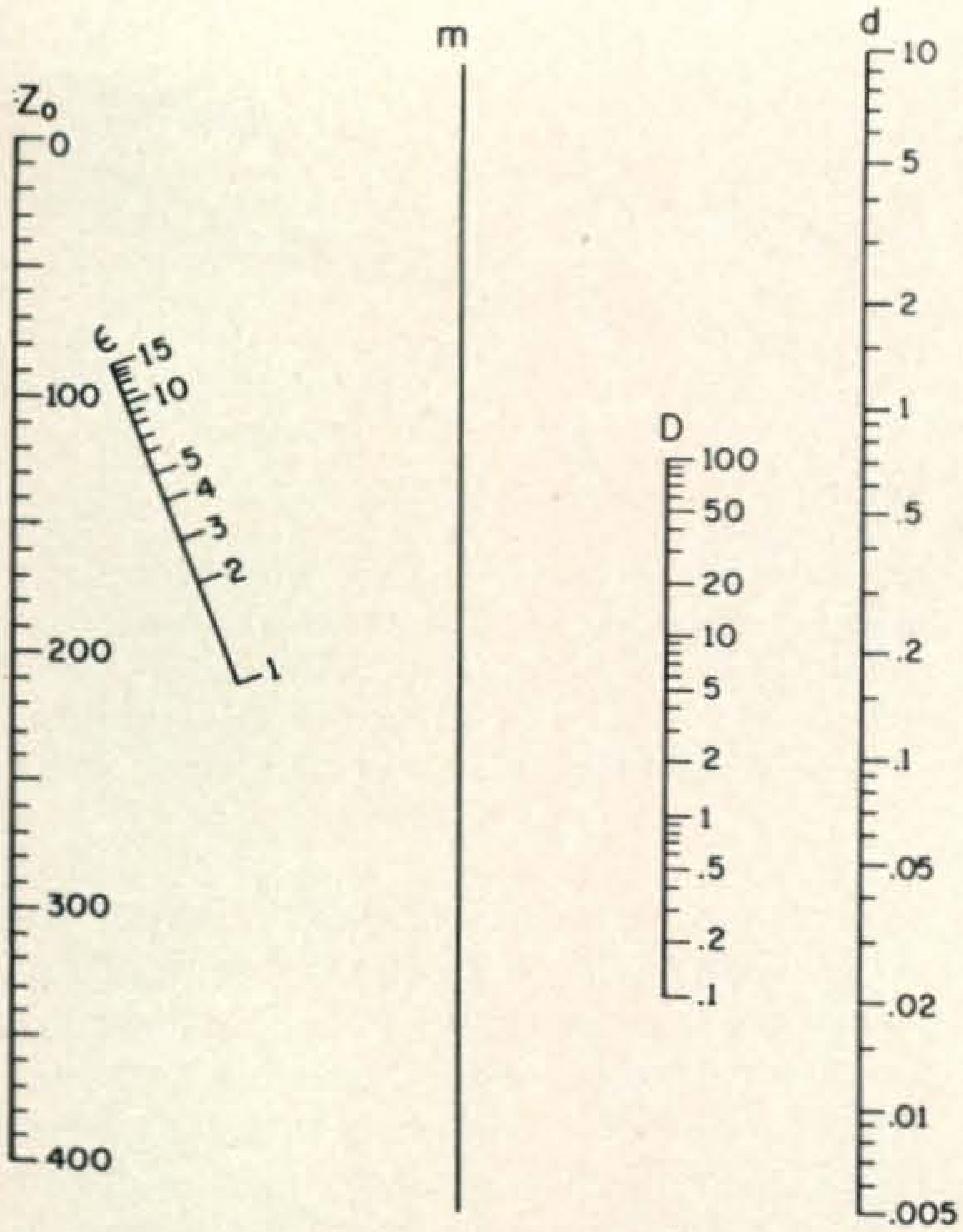

Fig. 7—Nomograph for determining the Z_0 of a solid dielectric coax. The two step procedure is explained in the text

tween the conductors. In the insulated type, the dielectric is solid enough to keep the conductors evenly spaced, but flexible enough to bend easily around corners. In one type of insulated line, the two conductors are molded into the edges of a plastic ribbon. See fig. 3. The dielectric losses are higher than in a comparable open wire line, and the higher dielectric constant lowers the characteristic impedance.

Shielded Pair—A further development of the insulated two-wire line is the shielded pair. See fig. 4. The two parallel conductors are imbedded in a solid dielectric. The insulated pair then is enclosed in a tube made of braided copper. The principal advantage of the shielded pair over other types of two-wire lines is its low radiation loss. This is true because the shield provides a uniform ground for both conductors, resulting in a well balanced line. Furthermore, the shield provides protection from stray pickup in the presence of external fields.

Twisted Pair—If two insulated wires are twisted together, a flexible transmission line results without the use of spacers. This type is limited to use as a short untuned line because of its high losses.

Coaxial Lines—It is possible to place one conductor inside the other to form a transmission line. Such a line is called coaxial, or concentric. The open line (air dielectric) is shown in fig. 5. Usuallly, it consists of a wire conductor placed inside a flexible metal tube or shield which serves as the second conductor. The inner wire is fixed along a central axis of the outer tube by spacers. The open coaxial line is used to provide efficient operation at relatively high frequencies. There is little radiation loss from this type of line because the outer conductor confines radiation to the space inside the line. External objects consequently have no effect on transmission, making this line definitely superior to the two wire type. Instead of air, the line can be filled with a flexible dielectric, forming a solid, coaxial line which has the advantage of greater flexibility compared with an open coaxial line. The use of a solid dielectric, however, increases the dielectric losses. The characteristic impedance of the open coaxial line can be calculated from the formula:

$$Z_0 = 138 \log_{10} D/d$$

where D = inner diameter of shield
d = wire diameter.

Variations in Z_0 with changes in the ratio D/d are given in fig. 6. The formula for Z_0 of a solid coaxial line is given by:

$$Z_0 = \frac{138}{\sqrt{\varepsilon}} \log_{10} D/d$$

where ε = dielectric constant of the materia[l] between the conductors.

The other quantities are the same as for the open coaxial line. If ε is equal to 1 (the dielectric constant of air), the two formulas formulas become identical. From both for[mulas] it can be seen that a high ratio of D/d means a high Z_0, and conversely, a low ratio means a low Z_0.

The designer of communications and electronics systems is often involved with determining characteristic impedances of concentric lines so as to properly match them to impedances of electronic instruments, meters *etc.* The nomogram of fig. 7 solves the above equation for any scale of dimensions.

Example: What is the characteristic impedance of a coaxial line if the wire diameter *d*, is (0.06) centimeters, the inner diameter o[f] the shield, *D*, is (0.85) centimeters, and th[e] dielectric constant of the material (ε) between conductors is (4.0)?

Solution: 1) Connect (*d*) with (*D*), intersec[t] (*m*). 2) Connect (*m*) with (ε), find Z_0 equa[l] 80 ohms.

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