CP 321
PRICE 10c

THE AUSTRALIAN POST OFFICE

COURSE OF TECHNICAL INSTRUCTION

Engineering Training Section, Headquarters, Postmaster-General's Department, Melbourne C.2.

CHARACTERISTICS OF R.F. TRANSMISSION LINES

1. INTRODUCTION.

1.1 Transmission lines are metallic conductors used for transmitting or guiding electrical energy from one point to another with minimum loss. They are used at radio frequencies to transfer energy from the transmitter output to the transmitting aerial, or from the receiving aerial to the receiver input. Short lengths of transmission line may be used for coupling between different stages of R.F. equipment.

1.2 Many types of R.F. transmission lines are in use, both open wire and cable, which may be either unshielded or shielded; and in either balanced form (with both sides of the line balanced to earth) or unbalanced form (with one side connected to earth).

1.3 This Paper revises and extends the transmission line theory given in the Course Paper "Transmission Line Characteristics", particularly as applied to radio frequencies. It briefly describes the types of lines used in the Department, and gives details of their electrical characteristics, including some of the changes that occur with different signal frequencies and varying weather conditions.

Later Papers in this series cover wave propagation and behaviour of R.F. transmission lines of different lengths and with different terminations, including applications of these lines.

The waveguide, a type of transmission line used to transmit r.f. energy at microwave frequencies, is discussed in other Papers of this Course.

2. TYPES OF LINES.

2.1 R.F. transmission lines may be grouped broadly as follows:-

(i) single wire line;
(ii) two wire parallel line;
(iii) twisted pair;
(iv) shielded pair;
(v) multi-conductor;
(vi) coaxial (or concentric) cable.

2.2 Each type of line has certain advantages and disadvantages compared to the other types. Some factors which determine the choice of line for a particular application, are:-

(i) The frequency band to be transmitted. Lines which are suitable for the transmission of frequencies in the M.F. and H.F. ranges, may not be satisfactory at higher frequencies.

(ii) The characteristic impedance. This is important in considering the impedance matching conditions between the source of energy and the line, and between the line and the load. (See Section 5, Characteristic Impedance). Correct impedance matching reduces losses due to reflection and ensures maximum transfer of energy from source to load.

(iii) The power-handling ability. This is related to the physical dimensions of the line. In the milliwatt range, small size conductors and close spacing are permissible; but when watts or kilowatts of power are to be transmitted, the size and spacing of the conductors must be increased accordingly.

(iv) Attenuation. Every line has some loss, depending on its type of construction, length and frequency of transmission. In general, the attenuation consists of losses due to conductor resistance, dielectric and radiation. These losses increase with frequency and are covered in more detail in Section 7, Attenuation and Line Losses.

(v) Interference and Radiation. Some types of lines are more susceptible than others in picking up stray R.F. interference from external sources. This is undesirable, particularly when the line is used to convey low level signals (for example, between a receiving aerial and a radio receiver) because it reduces the signal to noise ratio.

Similarly, when used between a radio transmitter and a transmitting aerial, these lines radiate energy which produces radiation losses and reduces the power supplied to the aerial. This radiated energy may cause interference in nearby R.F. transmission lines.

In the case of open wire construction, interference and radiation is reduced by careful attention to line construction and by maintaining a good line balance to earth and nearby objects. The use of shielded cables further reduces this effect.

(vi) Ease of handling. Size, weight and flexibility must be considered when supporting transmission lines, or when fitting lines in equipment where space is limited. Cable connectors, which depend on the type and size of the cable, are another important factor.

(vii) Environmental Conditions. These factors apply mainly to open wire lines, and include the effects on the line of the sun's radiation, chemical air pollution and weather conditions such as temperature extremes, humidity, wind, rain and snow.

(viii) Installation and maintenance. Open wire lines are cheaper to construct than coaxial lines, but they are more vulnerable to external faults caused, for example, by effects of weather and lightning discharges. However, these faults may be quickly detected and repaired.

Coaxial lines, particularly when buried underground, may suffer from corrosion with the possibility of moisture entering the line. Faults on coaxial cables are usually more difficult to locate and repair.

2.3 The single wire line is the simplest type; but it is not used in Departmental R.F. installations. This type of line is unbalanced using a single conductor with earth return. Losses by radiation are great and it will readily pick up R.F. interference. In this respect, the line behaves like a radio transmitting or receiving aerial.

2.4 The two wire parallel line is the basic type; and it is used for frequencies up to about 250MHz. Both wires are balanced with respect to earth and losses due to radiation are less than for the single wire line. To obtain a good line balance, the line must be of uniform construction throughout its length. Transposing the line wires or twisting the line also helps to improve the balance.

The open wire line (Fig. 1) is of similar construction to standard telephone lines but with poles at closer intervals. The two conductors of similar diameter are uniformly spaced and arranged horizontally so that they are carried at a uniform height (usually 8' or higher) above ground.

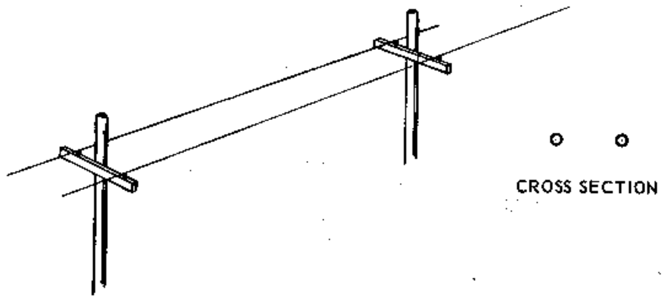


FIG. 1. OPEN WIRE TRANSMISSION LINE.

For short runs, low loss insulating spacers, or spreaders, may be used at suitable intervals to support and insulate the bare-wire parallel conductors (Fig. 2a).

Another method of ensuring uniform spacing is to embed the conductors in a low loss dielectric (for example, polyethylene) along the length of the line (Fig. 2b). In some lines, the dielectric is "slotted". This type of line is often called a flat, or ribbon, twin lead. It has the advantages of light weight, close and uniform spacing, and flexibility. The attenuation is higher than for two wire lines with air dielectric, and the line is suitable for carrying small power only. A typical use is the "feeder" line used to connect a T.V. receiving aerial to the input circuit of a T.V. receiver.

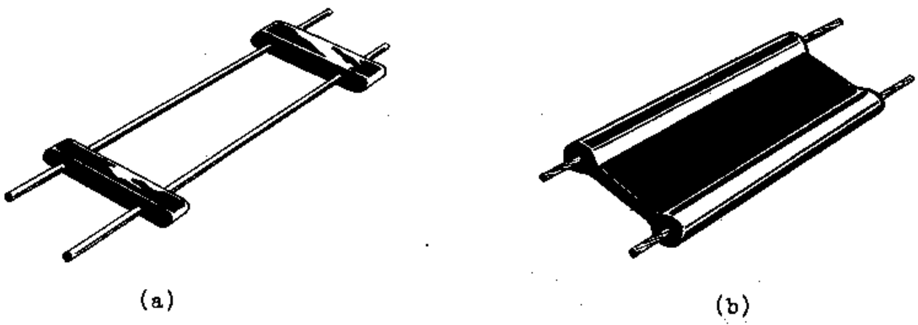


FIG. 2. TWO WIRE TRANSMISSION LINES.

The main disadvantage of a parallel wire transmission line is that nearby objects such as ground and buildings, etc., affect its balance and increase its radiation losses. This effect increases with frequency.

2.5 A twisted pair transmission line (Fig. 3) consists of two insulated wires twisted together to form a flexible line without the use of spacers. The separation between the wires is very small and radiation from the line is less than for a spaced two wire line. It is often used as a short link between stages in a transmitter.

This line is not used above about 15MHz because the insulation causes appreciable dielectric loss. Its chief advantage is that it may be used where more efficient lines are not possible because of space and mechanical considerations.

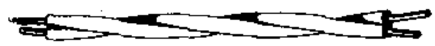


FIG. 3. TWISTED PAIR TRANSMISSION LINE.

2.6 The shielded pair transmission line (Fig. 4) consists of two parallel conductors separated and maintained a fixed distance apart by insulating spacers (for example, polystyrene), or surrounded entirely by an insulating dielectric material. The conductors are enclosed in a copper-braid tubing which acts as a shield. The outer layer consists of a plastic coating to protect the line against moisture and friction. The advantages of the shielded pair are that the two conductors are balanced to ground via the copper shield, which reduces radiation and pick-up of stray fields.

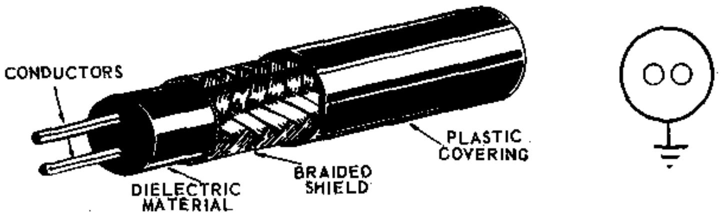


FIG. 4. SHIELDED PAIR TRANSMISSION LINE.

2.7 Multi-conductor open wire transmission lines may be used to carry high power at M.F. and H.F. transmitting stations.

In the four wire balanced line (Fig. 5a), the conductors are in the form of a square and each lower wire is connected to the wire immediately above. Alternatively, the diagonally opposite wires are connected together. This type of line has lower impedance, less attenuation and less radiation loss than the two wire balanced line.

In the six wire unbalanced line (Fig. 5b), the two inner wires are commoned to form the inner conductor, and the four outer wires are commoned and connected to earth to form the outer conductor. This constitutes an open wire coaxial line and is used, instead of the more costly coaxial cable, at some M.F. transmitting stations.

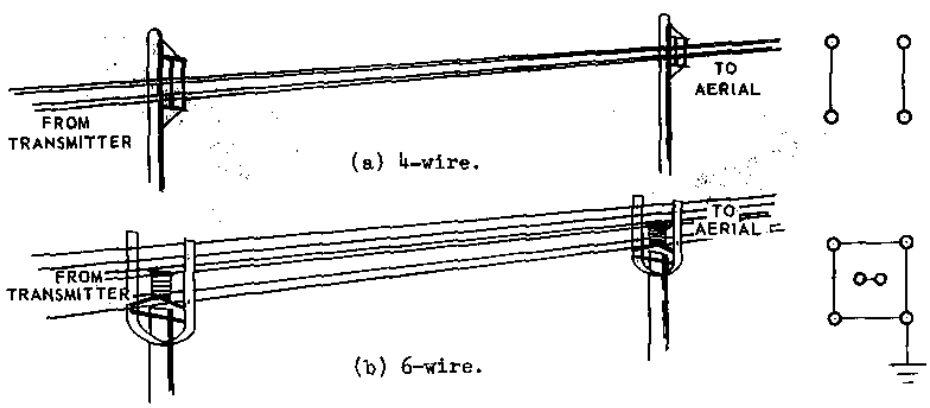


FIG. 5. MULTI-CONDUCTOR OPEN WIRE TRANSMISSION LINES.

2.8 The coaxial (or concentric) cable line consists of an inner conductor centrally located within, but insulated from, an outer conducting tube. The cable is unbalanced, the outer conductor being earthed.

In the rigid coaxial line (Fig. 6), the inner conductor is either solid or tubular, and is held in position by insulating disc spacers or beads at regular intervals. The spacers are made of pyrex, polystyrene or some other material with good insulating properties and low power loss characteristics at radio frequencies. This type of line is known as an air coaxial cable, and it must be kept dry to prevent excessive leakage between the conductors. Air dielectric lines, particularly when buried underground, are usually sealed at both ends and filled with a gas such as dry nitrogen under pressure, to prevent condensation of moisture and help keep the line dry. The power handling ability may be increased by pressurising the cable with an inert gas. Considerable care must be paid to the mechanical design of such a line to obtain airtight joints and to provide for expansion and contraction with temperature changes.

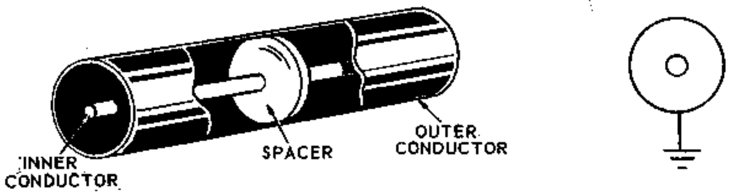


FIG. 6. AIR DIELECTRIC COAXIAL CABLE.

Coaxial cables are also made with the inner conductor of flexible wire which is insulated from the outer conductor by a solid and continuous insulating material such as polythene. (Fig. 7). This type of line is called a solid dielectric coaxial line. To provide flexibility, the outer conductor or shield consists of a plain or silver-covered copper braid which fits tightly around the insulating dielectric. A tough, flexible protective covering is fitted over the outer conductor.

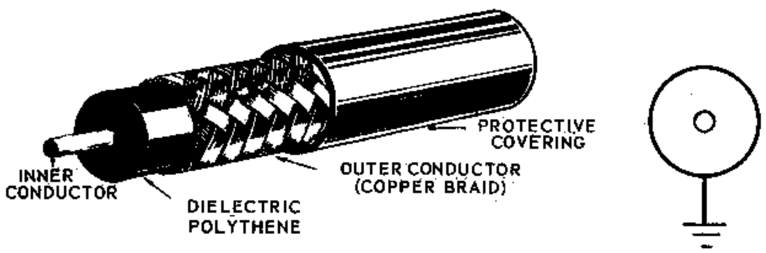


FIG. 7. SOLID DIELECTRIC COAXIAL CABLE.

A type of flexible coaxial cable used in the V.H.F. and U.H.F. ranges, is called a "helical membrane" cable. A typical cable consists of a solid inner conductor supported by an insulating material wound on edge into a helix. This gives adequate support to the inner conductor with a minimum of dielectric, and results in a low loss cable that has a degree of flexibility.

Due to the shielding provided by the earthed outer conductor, the electrical energy transmitted along a coaxial line is confined within the space between the two conductors, and losses due to radiation are negligible. Similarly, the energy contained in external fields does not penetrate the outer conductor and, therefore, does not induce interference in the coaxial line.

Provided the length is kept short and a very low loss dielectric is used, coaxial lines can be used at frequencies up to about 3,000MHz. Beyond this, even very short lengths of coaxial line introduce excessive attenuation.

Coaxial cable lines are more expensive to install than open wire lines; but they are capable of giving a superior performance, particularly at the higher frequencies.

3. LINE CONSTANTS.

3.1 Equivalent Circuit. In analysing the behaviour of a transmission line, it is convenient to regard it as consisting of one or more sections of unit length, measured in feet, yards or miles, etc. As shown in Fig. 8, each section may be represented electrically by an equivalent network containing:-

series resistance (R), expressed in ohms/unit length;
series inductance (L), expressed in henries/unit length;
shunt capacitance (C), expressed in farads/unit length;
shunt conductance (G), expressed in mhos/unit length.

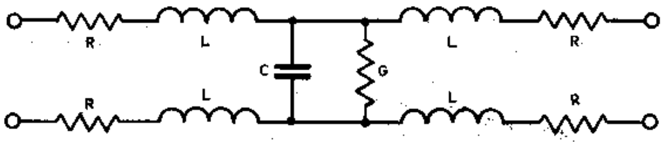


FIG. 8. EQUIVALENT CIRCUIT OF A TRANSMISSION LINE.

3.2 Effects of Primary Constants. These electrical properties of a line are called its primary constants; and they affect the r.f. signal as it travels along the line. For example:-

(i) the combination of resistive and reactive components indicates that the line possesses impedance;

(ii) the resistive components cause a progressive reduction in the strength of the signal along the line; and

(iii) the reactive components reduce the velocity at which the signal is propagated along the line.

3.3 Values of Primary Constants. The primary line constants are not "lumped" as in a conventional circuit. Instead, they are called distributed constants; that is, they are evenly spread or distributed along the entire length of the transmission line and cannot be distinguished separately. Their values increase with length of line, and may be expressed in terms of any unit of length. At radio frequencies, they are usually expressed in terms of either a 1,000 ft. or 100 ft. unit length of line.

The actual values vary for different types of lines and depend mainly on the physical configuration of the line and the dielectric material used in its construction. The values may also vary with frequency, temperature and weather conditions.

The electrical performance of a line (for example, its characteristic impedance, velocity of propagation and attenuation) can be calculated from the values of its primary constants, as indicated in Sections 5, 6 and 7.

3.4 The effective (or A.C.) series resistance at radio frequencies is much greater than the D.C. resistance of the line. This is due to the expanding and collapsing magnetic field within the line, which forces the alternating current to flow toward the outer surface or "skin" of the wire. This action, known as skin effect, reduces the total effective cross-sectional area of the wire, thereby increasing the series resistance. Skin effect increases with frequency.

The value of effective resistance depends on the size of the line conductors and is proportional to the square root of the frequency of the transmitted signal. For example, a 1,000 ft. length of 200 lb. H.D.C. wire has:-

a D.C. resistance of 1.67 ohms;
an effective resistance of about 13 ohms at 0.5MHz; and
an effective resistance of about 130 ohms at 50MHz.

Fig. 9 shows how effective resistance varies with frequency for various line wires.

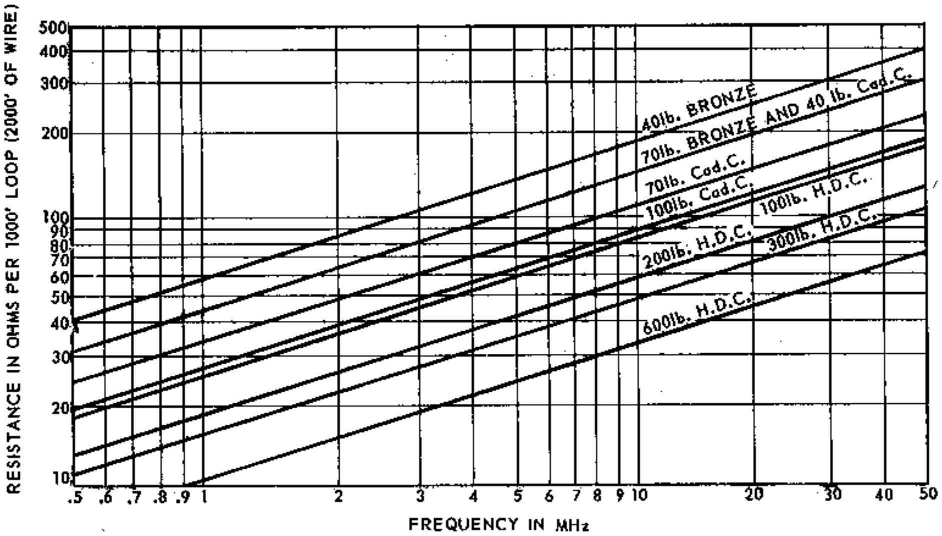


FIG. 9. RADIO FREQUENCY RESISTANCE OF VARIOUS LINE WIRES.

3.5 The series inductance depends on the size and spacing of the line conductors. For a given spacing, it increases with smaller size conductors; and for given size conductors, it increases as the line spacing is increased.

For a particular line, the value of series inductance remains fairly constant at radio frequencies. Typical values for a 1,000 ft. length of line, are:-

about 0.6mH to 0.8mH for a two conductor, open wire line;
about 0.15mH to 0.25mH for a two wire cable;
about 0.08mH to 0.12mH for a coaxial cable.

3.6 The shunt capacitance depends on the size and spacing of the line conductors, and also on the dielectric constant of the material between the line conductors. For a given spacing, it decreases with smaller size conductors; and for given size conductors, it decreases as the line spacing is increased.

For a particular line, the value of shunt capacitance remains fairly constant at radio frequencies. Typical values for a 1,000 ft. length of line, are:-

about 0.0015μF to 0.002μF for a two conductor, open wire line;
increasing to about 0.03μF for a cable with solid dielectric; and
about 0.015μF for a coaxial cable with air dielectric.

3.7 The shunt conductance of the dielectric between the line conductors produces losses at radio frequencies. Its value is greater than the conductance due to the D.C. insulation resistance of the line, and increases in proportion to frequency.

Shunt conductance (and, therefore, the effective shunt A.C. resistance) varies over a wide range with different types of line construction. In the case of open wire lines, it also varies with changing weather conditions. Typical values for a 1,000 ft. length of coaxial cable with air dielectric, are:-

2 micromhos at 0.5MHz;
20 micromhos at 5MHz;
200 micromhos at 50MHz.

The shunt conductance and the dielectric loss of solid dielectric cables are much higher.

4. INPUT AND OUTPUT IMPEDANCES.

4.1 A basic application of a transmission line is to supply energy from a generator to a load (Fig. 10a). In practice, at a transmitter installation, the radio transmitter is the generator and the transmitting aerial is the load (Fig. 10b). Similarly, at a receiver installation, the receiving aerial simulates the generator and the radio receiver is the load. (Fig. 10c).

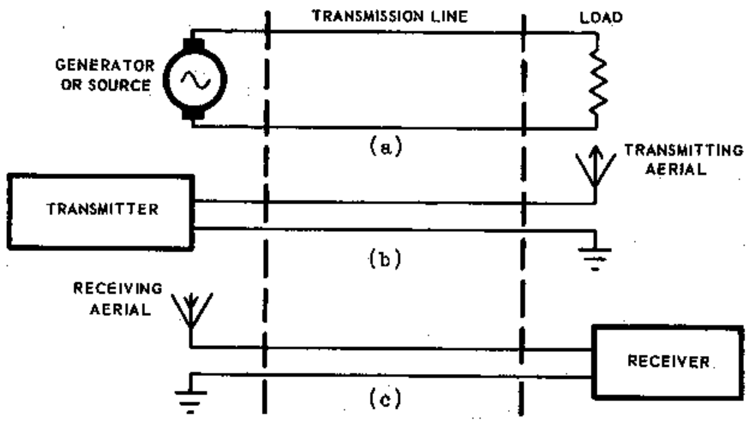


FIG. 10. APPLICATIONS OF TRANSMISSION LINES.

All transmission lines have two ends - input and output.

The input is the end where the signal energy is injected. This is also called the sending end, the generator end or the source end.

The output is the end from which energy is extracted. This is sometimes called the receiving end, load or terminating end.

4.2 A transmission line can be described in terms of its input and output impedances.

The input impedance is the impedance presented to the source by the line and its load; that is, the impedance "seen" by the generator at the input end looking down the line toward the load. Its value is equal to the ratio of voltage to current at the input end.

The output impedance is the impedance presented to the load by the line and its source; that is, the impedance "seen" at the output end looking back along the line toward the source. Its value is equal to the ratio of voltage to current at the output end.

4.3 For maximum transfer of energy from a generator to a load, the impedances of the generator and load must either be equal or be "matched" by a transformer or other matching device. When this is applied to the transmission of energy over a line, the following conditions must be observed:-

(i) The generator impedance must match the input impedance of the line, to ensure maximum transfer of energy from generator to line; and

(ii) the output impedance of the line must match the load impedance, to ensure maximum transfer of energy from line to load.

When these impedance are not matched, some of the energy is reflected back to the generator from the point of mismatch; and maximum energy is not absorbed by the load.

5. CHARACTERISTIC IMPEDANCE.

5.1 Each line has a value of impedance which is a characteristic of its particular construction. The input impedance (Zin) of an infinitely long transmission line is called its characteristic impedance (Zo). This is the value of impedance which determines the amount of current that can flow when a given voltage is applied to an infinitely long line (Fig. 11a). Some text books refer to Zo as surge impedance or iterative impedance.

In practice, a line need not be infinitely long for Zin to equal Zo. Provided any length of line is terminated in a load impedance (Z_L) equal to the Zo of the line, then Zin = Zo, irrespective of the length of the line (Fig. 11b). Further information on characteristic impedance is given in the Course Paper "Transmission Line Characteristics".

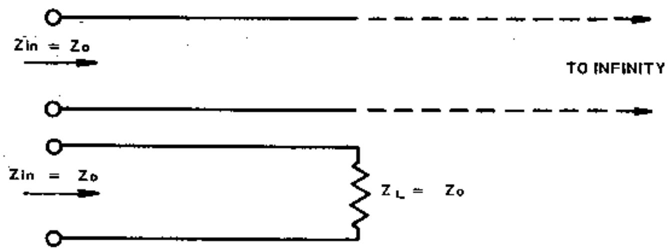


FIG. 11. INPUT IMPEDANCE OF TRANSMISSION LINES.

5.2 The characteristic impedance of a transmission line is important in ensuring that maximum energy is transferred from a generator to its load.

For example, to transfer maximum energy from transmitter to line in a transmitter installation (Fig. 10b), the output impedance of the transmitter must be matched to the input impedance of the line. Similarly, to transfer maximum energy from line to aerial, the aerial impedance must match the output impedance of the line.

A similar analysis applies at a receiver installation (Fig. 10c) where the impedance of the receiving aerial, Zo of the transmission line and input impedance of the receiver must all be matched.

5.3 Factors which determine value of Zo. In terms of the primary line constants, it can be proved that:-

$$Zo = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

At radio frequencies, ωL is very much greater than R, and ωC is very much greater than G, so that R and G can be neglected. The formula then simplifies to:-

$$Zo = \sqrt{\frac{j\omega L}{j\omega C}} = \sqrt{\frac{L}{C}}$$

where Zo is the characteristic impedance in ohms; L is the inductance in henries per unit length; and C is the capacitance in farads per unit length.

Any factor (such as size and spacing of line conductors, and type of dielectric used) which varies the series inductance or shunt capacitance of a line, will also vary its value of Zo. Using smaller size line conductors and/or increasing the conductor spacing, increases the inductance and decreases the capacitance, thus increasing the Zo of the line. The greater the dielectric constant of the insulating medium between the conductors, the higher the capacitance and the lower the Zo.

Referring to the simplified formula for Zo above, it is important to note that the values of L and C remain fairly constant at radio frequencies. This means that the value of Zo for a particular line does not vary greatly with frequency. In practice, it is usual to regard the Zo of an R.F. transmission line as being purely resistive.

5.4 Example No. 1. A typical 200 lb. H.D.C. open wire line has a series inductance of 0.66mH per 1,000 ft. and a shunt capacitance of 0.0018μF per 1,000 ft. Calculate the characteristic impedance of this line at radio frequencies.

Solution.

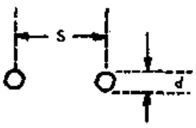
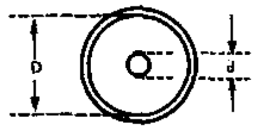
$$Zo = \sqrt{\frac{L}{C}}$$

$$= \sqrt{\frac{0.66 \times 10^{-3}}{0.0018 \times 10^{-6}}} = \sqrt{\frac{660 \times 10^{4}}{18}}$$

$$= \sqrt{36.67 \times 10^{4}} = 6.05 \times 10^{2} = 605 \text{ ohms.}$$

Answer = *605 ohms.*

5.5 Calculating Zo from dimensions of line. We can also calculate the value of Zo at radio frequencies from the cross-sectional dimensions of the line.

<table>
<tr><th>For a two wire line -</th><th>For a coaxial line -</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>$Zo \text{ (in ohms)} = \frac{276}{\sqrt{k}} \log_{10} \frac{2S}{d}$</td><td>$Zo \text{ (in ohms)} = \frac{138}{\sqrt{k}} \log_{10} \frac{D}{d}$</td></tr>
<tr><td>where S is the spacing between the centres of the conductors;
d is the diameter of a conductor;
both expressed in the same unit.</td><td>where D is the inside diameter of the outer conductor;
d is the outside diameter of the inner conductor;
both expressed in the same unit.</td></tr>
<tr><td colspan="2">In the above formulas, k is the dielectric constant of the insulating medium between conductors. For air dielectric and for all gases, k is taken as 1.</td></tr>
</table>

5.6 Example No. 2. What is the characteristic impedance at R.F. of an air dielectric coaxial cable with the following dimensions:-

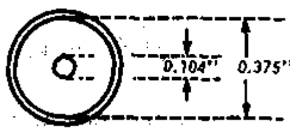
inside diameter (D) of outer conductor = 0.375 inch;
outside diameter (d) of inner conductor = 0.104 inch?

Solution. *As the cable has air dielectric, k = 1; and the formula simplifies to:-*

$$Zo = 138 \log_{10} \frac{D}{d}$$

$$= 138 \log \frac{0.375}{0.104} = 138 \log 3.6$$

$$= 138 \times 0.5563 = 76.8 \text{ ohms.}$$



Answer = *76.8 ohms.*

5.7 Optimum Ratio of D/d. In the design of coaxial cables, when the ratio D/d is plotted against attenuation per unit length, minimum attenuation is found to occur when the ratio equals 3.6. This ratio gives a Zo of about 75 ohms for air dielectric cables, and about 50 ohms for a solid dielectric such as polythene. The minimum in the attenuation curve is very broad, however, and for ratios of 2.5 and 6, the loss is only about 10% greater than with the optimum of 3.6.

5.8 Graphs of Zo. We can plot the equations given in para. 5.5, as graphs which relate Zo to the ratio of the dimensions (Fig. 12).

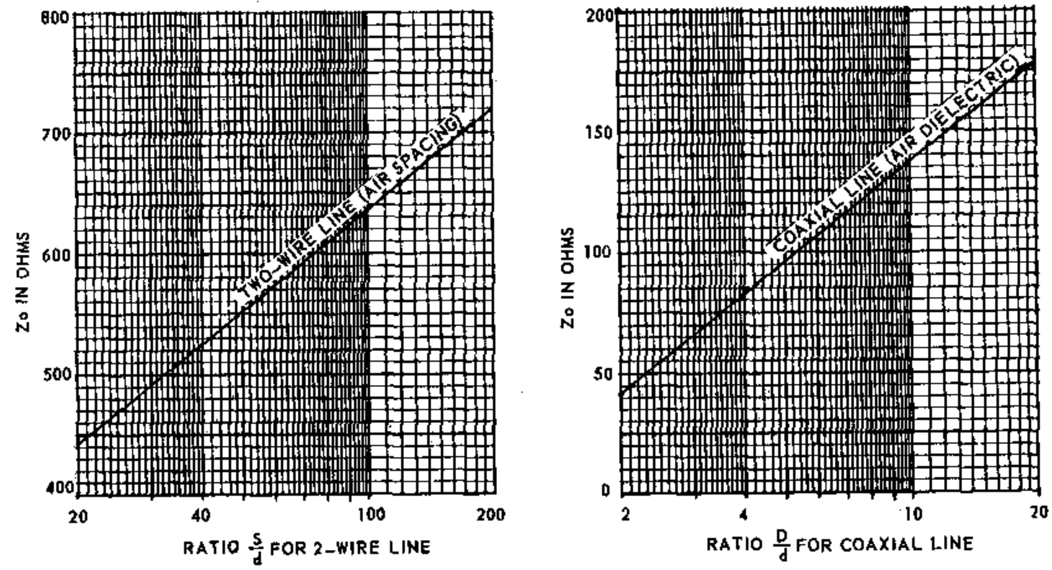


FIG. 12. GRAPHS OF Zo FOR TWO WIRE AND COAXIAL LINES.

These graphs apply to lines with air dielectric. For solid dielectric lines, multiply the value of Zo (as obtained from the graphs) by a factor:-

$$\frac{1}{\sqrt{k}},$$ *where k is the dielectric constant of the insulation.*

Typical values of k for polyethelene, polystyrene and polythene range from about 2.3 to 2.9.

Note that, for similar ratios of cross-sectional dimensions, a line with a solid dielectric has a lower Zo than one with air dielectric.

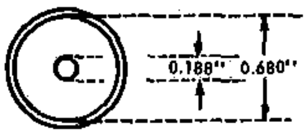
5.9 Example No. 3. Using the graph for a coaxial line in Fig. 12, calculate the Zo of a coaxial cable with the following dimensions:-

inside diameter (D) of outer conductor = 0.680 inch
outside diameter (d) of inner conductor = 0.188 inch;

assuming (i) air dielectric; (ii) a solid dielectric (k = 2.25).

Solution. *(i) Determine the ratio* $\frac{D}{d} = \frac{0.680}{0.188} = 3.6$

From Fig. 12b, this ratio gives a Zo of about 75 ohms.



(ii) For the solid dielectric cable, multiply this value of Zo = 75 ohms, by:-

$$\frac{1}{\sqrt{k}} = \frac{1}{\sqrt{2.25}} = \frac{1}{1.5}$$

Therefore, $Zo = \frac{75}{1.5} = 50$ *ohms.*

Answers = *(i) 75 ohms; (ii) 50 ohms.*

5.10 Determining Zo by measurement. The characteristic impedance of a line can also be obtained by measurement. This is done by measuring the input impedance of the line with the receiving end open circuited (Zoc), and then with the receiving end short circuited (Zsc). The characteristic impedance is obtained from the formula:-

$$Zo = \sqrt{Zoc \times Zsc}$$

5.11 Nominal values of Zo. At radio frequencies, the Zo of a particular transmission line is fairly constant and can be considered to behave as a pure resistance. For R.F. transmission lines used in practice, it usually lies between 50 ohms and 600 ohms. Approximate values are:-

(i) open wire line (2 wire)	:	600 ohms.
(ii) open wire line (4 wire)	:	300 ohms.
(iii) open wire line (6 wire)	:	200 ohms.
(iv) coaxial line	:	50 ohms or 75 ohms.

Transmission lines are often described in terms of their Zo; for example, in the expressions:-

"a 600 ohm open wire line" and "a 75 ohms coaxial cable",

the reference to 600 ohms and 75 ohms indicates the nominal value of Zo for the particular line.

5.12 Use of lines with low Zo. Multiple conductor open wire lines, because of their lower values of Zo, are preferred to two conductor open wire lines for the transmission of large R.F. powers. When transmitting a given power, the voltage between conductors is less for lines of lower Zo, and this reduces the risk of insulation breakdown and arcing. This is shown in Example No. 4. Note that, for lower values of Zo, although the voltage between conductors is less, the current in the conductors is increased. The increased current may tend to overheat the conductors; but, in practice, this can be avoided by using heavy gauge line wires.

5.13 Example No. 4. A 100kW transmitter is matched to an aerial via a transmission line. Assuming 100% modulation, calculate the peak values of the voltage across and the current in the line conductors when the Zo of the line is:-

(i) 600 ohms; (ii) 300 ohms.

Solution. *(i) For a carrier power of 100kW (unmodulated) the R.M.S. value of voltage across the 600 ohm line:-*

$$E = \sqrt{P \times Zo} = \sqrt{100,000 \times 600} \text{ volts.}$$

Multiply this value by $\sqrt{2}$ to convert to peak volts (unmodulated), and then by 2 to convert to peak volts (modulated 100%).

Then, $$E_{max} \text{ (modulated 100\%)} = 2\sqrt{100,000 \times 600 \times 2}$$
$$= 2\sqrt{120 \times 10^{8}} = 2,000\sqrt{120}$$
$$= \underline{22,000 \text{ volts}} \text{ (approx)};$$

and $$I_{max} \text{ (modulated 100\%)} = \frac{E_{max}}{Zo} = \frac{22,000}{600} = \underline{36.5 \text{ amperes}} \text{ (approx)}.$$

(ii) A similar analysis for a Zo of 300 ohms, produces values of:-

$$E_{max} \text{ (modulated 100\%)} = \underline{15,500 \text{ volts}} \text{ (approx)};$$

and $$I_{max} \text{ (modulated 100\%)} = \underline{51.6 \text{ amperes}} \text{ (approx)}.$$

Answers = *(i) 22kV and 36.5A; (ii) 15.5kV and 51.6A.*

6. PROPAGATION CHARACTERISTICS.

6.1 Velocity of Propagation. R.F. energy is propagated at a maximum velocity of 300×10^6 metres per second (or 186,000 miles per second) in free space. This velocity is reduced in an R.F. transmission line by a factor (see para. 6.4) depending on the type of dielectric used for spacing and supporting the particular line. At radio frequencies, the velocity of propagation is largely independent of frequency.

The velocity of propagation (V) can be calculated from the formulas:-

(i) $V = \dfrac{300 \times 10^6}{\sqrt{k}}$ metres per second;

(ii) $V = \dfrac{186{,}000}{\sqrt{k}}$ miles per second;

(iii) $V = \dfrac{1}{\sqrt{LC}}$

In (i) and (ii), k is the dielectric constant of the insulating material.

In (iii) the same unit of length is used to express the velocity as that for which L and C are given.

6.2 Example No. 5. Calculate the velocity of propagation along a coaxial cable line with solid polythene dielectric, assuming a dielectric constant of 2.25.

Solution. $V = \dfrac{186{,}000}{\sqrt{k}}$ miles/second

$$= \frac{186{,}000}{\sqrt{2.25}} = \frac{186{,}000}{1.5} = 124{,}000 \text{ miles/second.}$$

Answer = 124,000 miles/second.

6.3 Example No. 6. Calculate the velocity of propagation along a line which has the following constants per 1,000 ft. length of line:-

$$L = 0.1\text{mH} \quad : \quad C = 0.0144\mu\text{F}$$

Solution. *To simplify calculations, convert these values to basic units (henry and farad) per 1 mile length of line.*

$$L = (0.1 \times 5.28 \times 10^{-3}) \text{ henry/mile}$$

$$C = (0.0144 \times 5.28 \times 10^{-6}) \text{ farad/mile}$$

$$V = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{0.1 \times 5.28 \times 10^{-3} \times 0.0144 \times 5.28 \times 10^{-6}}} \text{ miles/second.}$$

$$= \frac{1}{\sqrt{0.00144 \times 10^{-9} \times (5.28)^2}}$$

$$= \frac{1}{5.28 \sqrt{144 \times 10^{-14}}} = \frac{10^7}{5.28 \times 12}$$

$$= \frac{10^7}{63.36} = 158{,}000 \text{ miles/second.}$$

Answer = 158,000 miles/second.

6.4 Velocity Factor. The velocity of propagation of electromagnetic waves along a transmission line, is less than that in free space. The ratio of the velocity along a given line to the velocity in free space, is called the velocity factor.

For example, the velocity factors of the lines referred to in Examples 5 and 6, are:-

$$\frac{124,000}{186,000} = 0.67 \text{ and } \frac{158,000}{186,000} = 0.85 \text{ respectively}$$

Typical values for various transmission lines are shown in Table 1.

Type of Line	Velocity Factor
Open wire line with air dielectric	0.95 - 0.975
Coaxial line with spacers and air dielectric	0.85
Coaxial line with solid dielectric	0.65
Two wire line with plastic dielectric	0.68 - 0.82
Twisted pair line with rubber dielectric	0.56 - 0.65

TABLE 1. VELOCITY FACTORS FOR TYPICAL LINES.

6.5 Wavelength. Because the velocity of propagation is less than in free space, the distance occupied by one cycle of a current or voltage wave on an R.F. transmission line (that is, the wavelength) is less than the wavelength in free space. For example, at a frequency of 10MHz:-

$$\text{Wavelength } (\lambda) = \frac{\text{Velocity}}{\text{Frequency (Hz)}} = \frac{300 \times 10^6}{10 \times 10^6} = 30 \text{ metres in free space;}$$

but, on an open wire transmission line, λ = about $30 \times 0.95 = 28.5$ metres;

and on a coaxial line with solid dielectric, λ = about $30 \times 0.65 = 19.5$ metres.

This effect is summarised in Fig. 13. Note that the reduced velocity decreases the wavelength, but does not affect the frequency.

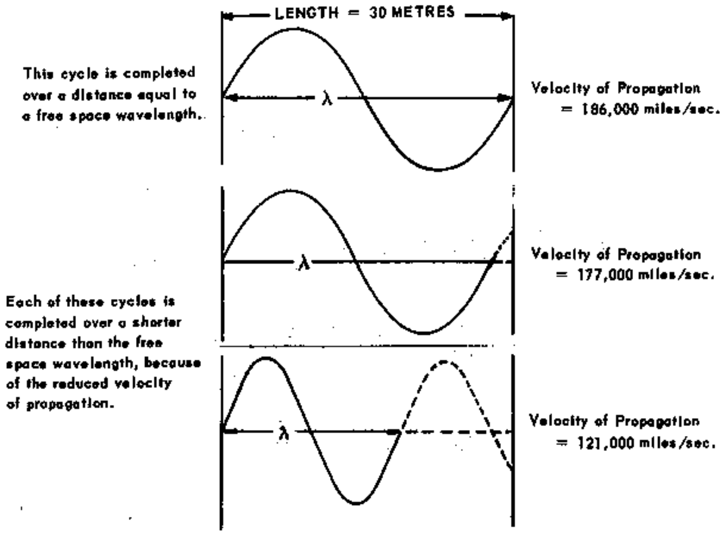


FIG. 13. EFFECT OF REDUCED VELOCITY ON WAVELENGTH.

6.6 Electrical Length. Whenever reference is made to the length of a line in terms of its wavelength at a particular frequency, this refers to its electrical length. Lines which have the same electrical length at a particular frequency may have different physical lengths because of the different velocities of propagation.

Thus, a line which has an electrical length of one wavelength at a frequency of 10MHz, has a physical length of:-

about 28.5 metres for an open wire line and
about 19.5 metres for a solid dielectric coaxial line.

6.7 Electrically Long and Short Lines. The electrical length of a line is determined by the frequency of the applied signal and the velocity of propagation along the line. The terms "long" and "short" are sometimes used to describe the electrical length of a line. Lines longer than one wavelength on which a complete cycle may be generated at a source before the energy at the start of the cycle reaches the load, are said to be electrically long. Lines less than one wavelength are electrically short.

For example, at a frequency of 10MHz, a line 60 metres long has an electrical length of 2 wavelengths (neglecting the velocity factor), and is considered to be electrically long; but when the line is reduced to 7.5 metres, the electrical length is one-quarter wavelength, and this line is electrically short. Similarly, a line of 7.5 metres is electrically long at frequencies above about 40MHz; but in the higher microwave frequencies, conductors of even a few inches are considered to be electrically long.

6.8 Example No. 7. (i) What is the wavelength in space of an electromagnetic wave which has a frequency of 750kHz?

(ii) What is the wavelength of this wave on a coaxial line which has a velocity factor of 0.85?

Solution. (i) *Wavelength* $= \frac{\text{Velocity}}{\text{Frequency}} = \frac{300 \times 10^6}{750{,}000} = \underline{400 \text{ metres}}.$

(ii) First find the velocity of propagation on the line:-

$$\text{Velocity} = \text{Velocity in free space} \times \text{Velocity Factor}.$$

$$= 300 \times 10^6 \times 0.85 \text{ metres/sec.}$$

$$\text{Wavelength} = \frac{\text{Velocity}}{\text{Frequency}} = \underline{340 \text{ metres}}.$$

Answers = (i) 400 metres ; (ii) 340 metres.

6.9 Example No. 8. Calculate the physical length of a transmission line which has a velocity factor of 0.9 and is one-half wavelength long at a frequency of 150MHz.

Solution. Calculate the physical length for $\frac{\lambda}{2}$, *assuming velocity of propagation in free space; then multiply this length by the velocity factor.*

$$\text{Wavelength in free space} = \frac{\text{Velocity}}{\text{Frequency}}$$

$$= \frac{300 \times 10^6}{150 \times 10^6} = 2 \text{ metres}.$$

$$\text{Therefore, } \frac{\lambda}{2} \text{ in free space} = 1 \text{ metre}.$$

$$\frac{\lambda}{2} \text{ on transmission line} = \frac{\lambda}{2} \text{ in free space} \times \text{Velocity Factor}$$

$$= 1 \text{ meter} \times 0.9 = \underline{0.9 \text{ metre}}.$$

Answer = 0.9 metre (or approx. 3 feet).

7. ATTENUATION AND LINE LOSSES.

7.1 Types of Losses. The main purpose of a transmission line is to deliver the entire transmitter output to the aerial or the entire received signal to the receiver. In practice, however, there is always some loss (attenuation) in a transmission line. Losses in R.F. transmission lines are due to:-

(i) conductor loss;
(ii) dielectric loss;
(iii) induction and radiation losses;
(iv) reflection loss.

7.2 Conductor loss. When current flows in a conductor, energy is dissipated in the form of heat. This is due to the effective A.C. resistance of the conductors; and is sometimes called a heating loss, a copper loss, a skin effect loss, a power loss or an I^2R loss.

Due to skin effect, R.F. currents tend to flow only in the outer surface of a conductor. Hence, a copper tube is just as effective for carrying high-frequency currents as a solid rod of the same diameter. The conductivity of an R.F. line can be increased by plating it with silver. Most of the current then flows in the silver layer, and the tubing serves mainly for mechanical support.

7.3 Dielectric loss is due to the heating of the dielectric material (insulation) between conductors, which takes power from the source. With mainly air spacing, as in open wire lines, this type of loss is kept to a minimum; and mainly occurs at the insulators used to mount and space the wires. In lines which use spacers or beads at regular intervals and in solid dielectric lines, the insulating medium is made of pyrex, polystyrene, polythene or some other material possessing good insulating qualities and low loss at radio frequencies.

7.4 Induction and radiation losses are similar and are both due to the electromagnetic field surrounding the conductors.

When this field cuts a nearby metallic object, a current is induced and power is dissipated by the object. The power thus lost is supplied by transformer action from the source for the R.F. line.

Radiation loss occurs because some of the field about a conductor does not return to it when the frequency cycle changes, but is projected into space as radiation. This additional power loss must be supplied from the source.

Radiation loss may be considerable in a two wire line but can be decreased either by reducing the spacing between wires or by shielding. Both methods increase the capacitance between wires, which is usually undesirable. For the least loss from this cause, coaxial cables are used because of their natural shielding.

This type of loss increases as the square of the frequency.

7.5 Reflection loss occurs when a line is not terminated in its characteristic impedance. In this case, not all of the energy arriving at the end of the line is dissipated in the termination, and some is reflected back along the line. This constitutes an effective loss of power from an overall point of view.

Similarly, reflection loss occurs at any point of impedance irregularity in line construction; for example:-

(i) at the points where open wire lines are attached to insulators;

(ii) at the insulating disc spacers in air dielectric coaxial cables.

In practice, it is important to maintain uniformity in line construction (as far as possible) to keep this type of loss to a minimum.

7.6 Effects of Weather. Open wire transmission lines are often subject to a wide range of weather variations which have significant effects on the properties of the lines. Cables lines are not usually affected by weather conditions, although they are affected by temperature changes.

The series resistance of an open wire line is increased under high temperature, and also under wet weather conditions. During wet weather, the film of moisture on the wires is slightly conductive. Since the magnetic field within the wires forces the current to flow more towards the surface, part of the current leaves the wire and flows in the film of water. The resistance of the water film is many times greater than the resistance of the copper wire. Similarly, during frosty or icy conditions, the coating of ice on the wires may become very thick with a considerable part of the current leaving the wire and flowing in the ice coating. These conditions increase the resistance loss due to increased skin effect.

Moisture and ice also affect the shunt conductance of the open wire line. When the weather is dry, the shunt conductance is low and the loss is relatively low. During wet weather, dirt and dust collect on the insulators which become much more conductive. The shunt conductance increases and more current flows through the shunt leakage paths, increasing the attenuation.

Under severe icing conditions, the attenuation caused by skin effect and shunt conductance may be increased by as much as six or more times normal dry weather attenuation.

7.7 Formulas. For low-loss lines at high frequencies:-

(i) the resistance loss varies as the square root of the frequency, and
(ii) the dielectric loss is directly proportional to the frequency.

The respective formulas are:-

Resistance loss in db per unit length $= \frac{4.34 \times R}{Zo}$

Dielectric loss in db per unit length $= 4.34 \times G \times Zo$

where R is A.C. (not D.C) resistance in ohms per unit length of the line at the operating frequency;

G is shunt conductance in mhos per unit length of the line at the operating frequency;

Zo is the characteristic impedance in ohms of the line.

7.8 Example No. 9. Calculate the total attenuation due to resistance loss and dielectric loss of a 100 ft. length of low-loss coaxial cable, which has the following characteristics at a frequency of 100MHz:-

Zo = 75 ohms ; R = 12 ohms ; G = 40 micromhos.

Solution. Calculate the resistance and dielectric losses separately, then add.

Resistance loss $= \frac{4.34 \times R}{Zo}$	*Dielectric loss* $= 4.34 \times G \times Zo$
$= \frac{4.34 \times 12}{75}$	$= 4.34 \times 40 \times 10^{-6} \times 75$
$= 0.7$*db (approx)*	$= 0.013$*db (approx).*

Total Loss = *Resistance loss + Dielectric loss*

$= 0.7 + 0.013 = 0.713$*db.*

Answer = *0.7db (approx).*

8. *TEST QUESTIONS.*

1. *What is the purpose of a transmission line when used:-*

   (i) between a radio transmitter and an aerial;
   (ii) between a radio receiver and an aerial?

2. *Briefly describe the construction of an air dielectric coaxial cable.*

3. *State the four electrical primary constants of a two wire line and the units in which they are expressed. Draw a diagram to show how a two wire line is considered to consist of these constants.*

4. *Why does the series A.C. resistance of a transmission line vary with frequency?*

5. *Assuming other factors constant, how is the series resistance of a two wire line affected when:-*

   (i) the frequency of the transmitted signal is increased;
   (ii) the size of the line conductors is increased?

6. *Assuming other factors constants, how is the series inductance of a two wire transmission line affected when:-*

   (i) the size of the conductors is increased;
   (ii) the line wires are brought closer together?

7. *Assuming other factors constant, how is the shunt capacitance of a two wire transmission line affected, when:-*

   (i) larger size conductors are used;
   (ii) a solid dielectric is used instead of air dielectric?

8. *At a certain frequency, the shunt conductance of a 1,000 ft. length of line, is 30 micromhos. What is the shunt conductance of a 1,500 ft. length of this line?*

9. *What is meant by the terms "input impedance" and "output impedance" as applied to R.F. transmission lines?*

10. *What is meant by the characteristic impedance of an infinite line? What symbol represents characteristic impedance?*

11. *What is the input impedance of a 50 ohm coaxial cable which is terminated in a load resistance of 50 ohms?*

12. *What is meant by the characteristic impedance of a line of definite length?*

13. *What is the condition for maximum transfer of energy from:-*

    (i) a generator to a line;
    (ii) a line to a load?

14. *Assuming other factors constant, how is the characteristic impedance of a two wire line with air spacing affected, when:-*

    (i) the line wires are spaced closer together;
    (ii) line wires of a smaller gauge are used;
    (iii) the wires are embedded in a plastic sheathing with a dielectric constant of 4?

15. *Assuming other factors are unaltered, what is the effect on the characteristic impedance of a coaxial line, when:-*

    (i) the gauge of the inner conductor is reduced;
    (ii) the inside diameter of the outer conductor is increased?

16. *What is the effect on the characteristic impedance of a coaxial line if the air dielectric is replaced by a dielectric of solid material?*

17. *Calculate the characteristic impedance, at radio frequencies, of a coaxial line which has a series inductance of 8μH per 100 ft. length and a shunt capacitance of 1,500pF per 100 ft. length.*

18. *Calculate the characteristic impedance of a transmission line which has input impedances of 1,210 ohms and 250 ohms with the receiving end open-circuited and short-circuited respectively.*

19. *In a coaxial cable, what ratio of outer to inner conductor diameters gives minimum attenuation?*

20. *Calculate the characteristic impedance of a coaxial cable of which the inner conductor is a ¼ inch diameter copper rod, and the outer conductor is a 7/8 inch diameter tubing (inside diameter).*

21. *Calculate the characteristic impedance of a solid dielectric (k = 2.25) coaxial line in which the inner diameter of the outer conductor is 0.75 inch, and the outer diameter of the inner conductor is 0.20 inch.*

22. *Calculate the characteristic impedance of a two conductor open wire line constructed of 200 lb. H.D.C. conductors (diameter 0.11 inch) spaced 8½ inches apart.*

23. *A 100kW transmitter is matched to an aerial via a line with a characteristic impedance of 200 ohms. Assuming 100% modulation, calculate the peak values of the voltage and current in the line. (Compare your answers with those given in Example No. 4 on page 12).*

24. *Why are four conductor open wire lines preferred to two conductor lines for the transmission of large R.F. powers?*

25. *Why is it important to maintain uniformity in the construction of transmission lines?*

26. *How is the dielectric loss of solid dielectric coaxial cables, kept to a minimum?*

27. *Calculate the total attenuation due to resistance loss and dielectric loss of a 1,000 ft. length of coaxial cable, which has the following characteristics at a frequency of 150MHz:-*

$Zo = 70$ ohms ; $R = 80$ ohms ; $G = 0.01$ mho.

28. *Why are open wire transmission lines not suitable for use at frequencies in the U.H.F. range?*

29. *Calculate the velocity of propagation along a two wire line, when the insulation between the wires has a dielectric constant of 2.*

30. *Calculate the velocity of propagation along a two conductor open wire line, which has a series inductance of 0.8mH/1,000 ft. and a shunt capacitance of 0.001μF/1,000 ft.*

31. *What is the wavelength in space of an electromagnetic wave which has a frequency of:-*

4MHz ; 15MHz ; 1,5GHz ; 6GHz?

32. *What is meant by the term "velocity factor" as applied to transmission lines? What is the effect on the velocity factor when the air dielectric of a transmission line is replaced with a solid dielectric?*

33. *What is meant by the term "electrical length" as applied to a transmission line?*

34. *An R.F. line has an electrical length of one-half wavelength at a frequency of 160MHz. What is its electrical length at a frequency of 80MHz?*

35. *An R.F. line is 2 wavelengths long at a frequency of 15MHz. What is the electrical length of this line at a frequency of 30MHz?*

36. *What is the velocity of propagation (in miles per second) on a transmission line which has a velocity factor of 0.75?*

37. *What is the physical length in metres of a transmission line which has an electrical length of one-half wavelength at a frequency of 20MHz, assuming a velocity factor of 0.9?*

38. *What is the velocity factor of an R.F. line which has a physical length of 2 metres, and is one-quarter wavelength long at a frequency of 30MHz?*

39. *An R.F. line with a velocity factor of 0.8, has a physical length of 12 inches. At what frequency will this line be one-quarter wavelength long? (Assume 1 metre = 40").*

40. *State four types of losses that can occur in R.F. transmission lines.*

41. *Why is hollow copper tubing just as effective as solid conductors for the transmission of energy along R.F. transmission lines?*

ANSWERS TO PROBLEMS.

8.	45 micromhos	29.	131,500 miles/sec.
11.	50 ohms	30.	172,000 miles/sec.
17.	73 ohms	31.	75 metres; 20 metres;
18.	550 ohms		0.2 metre; 5cm.
20.	75 ohms	34.	$\lambda/4$
21.	53 ohms	35.	4λ
22.	601 ohms	36.	139,500 miles/sec.
23.	12.65KV; 63.25A	37.	6.75 metres
27.	8db	38.	0.8
		39.	200MHz.

END OF PAPER.