# TRANSMISSION IMPROVEMENT ON LONG RURAL SUBSCRIBER TELEPHONE LOOPS

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by
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# CHAPTER I

# THE RURAL SUBSCRIBER LOOP TRANSMISSION PROBLEM

## 1. Introduction

Telephone service for the rural subscriber has been provided in the past on a manual, ringdown basis. Manual offices are inexpensive to install in small sizes. Hence the existing rural telephone system includes many scattered central offices each serving a few subscriber lines within a small geographic area.

The demand for a better grade of service forces conversion from manual to dial operation. Dial offices cannot be installed economically in sizes of less than a few hundred subscriber lines. Each dial office, therefore, replaces several magneto offices, and serves a much larger area than did a magneto office. In this larger area subscriber loops are longer. Thus the introduction of dial service lengthens the subscriber loops and increases their transmission loss. In practice the transmission objective is exceeded by as much as 10 db.

This study was undertaken to investigate the most economical methods by which transmission can be improved on the lengthened loops. It is directed particularly to the conditions existing in the Prairie Provinces since it is in this region that the problem is most prevalent. Steel open wire is the most common rural loop facility on the Prairies, and it is this facility which is considered in this paper.

For steel open wire the solution recommended involves two steps:

(a) Inductive loading of the loop to gain transmission improvement for medium length loops, and

(b) the installation of office mounted repeaters for additional improvement on the longest lines.

The advantages and limitations of each step are detailed in this report.

## 2. Subscriber Loop Design

A subscriber loop provides access to the switching office so that the subscriber may converse with any other subscriber. Dial service imposes two restrictions on the loop facility:

(a) Its dc resistance must not exceed the supervisory limit of the switching office, and

(b) its ac transmission efficiency must be acceptable to the subscriber.

The practical aspects of these restrictions are discussed in this section. This will provide a basis for the specification of the improvement required on long rural loops.

Supervisory limits are imposed by the characteristics of the office and by the voltage of the supply battery. The majority of Canadian installations employ loop dialling from a 48 volt supply. The supervisory range is then 1300 or 1500 ohms, although this range may be increased somewhat through the use of long line adapters and special high efficiency telephones. Both the supervisory current and the telephone transmitter current are supplied by the office battery in loop operation.

"Simplex" dialling is used on long rural lines to extend the supervision range to 5000 ohms.[1] The office battery is applied between the paralleled line conductors and ground, and is used for dialling and supervision only. Transmitter current is supplied from dry cells in the telephone set and is independent of the loop facility.

Transmission limitations cannot be defined so precisely since they depend upon the reaction of the subscriber. A "good" circuit is one which delivers to the listener's ear sufficient audio power of adequate bandwidth and with sufficiently low interference power that the listener is satisfied with the quality of the circuit. The power delivered depends in part upon the characteristics of the talker, the efficiency of the telephone sets, the effect of sidetone on the talker, and the effective loss of subscriber loops and trunk circuits. Of these factors an operating telephone company has direct control only over the type of telephone set and the transmission efficiency of subscriber loops and trunks.

Experimental methods have been used to establish the maximum effective loss between specified telephone sets which will provide a transmission quality satisfactory to the great majority of subscribers. This maximum loss has been allocated between subscriber loops and trunk circuits in a manner which ensures that it is not exceeded for any permissive circuit interconnection. Thus a maximum effective subscriber loop loss for any

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[1] See, for example, Alberta Government Telephones Descriptive Specification For Tenders Covering Community Dial Offices, Issue 2, Section C "Station and Line Design".

specific telephone set may be defined. A loop which just provides this grade of performance is called a limiting loop.

The engineering of a large number of subscriber loops demands a relatively simple procedure. The loop loss factor method provides such a procedure. It is a method by which the performance of a subscriber loop can be compared with that of a limiting loop.

Basically three variables are considered:

(a) the effective loss of the loop facility,

(b) the efficiency of the telephone sets, and

(c) the type of battery supply used for transmitter current.

The effective loss of the facility depends, of course, upon its total attenuation - frequency characteristic. This loss per unit length of facility is calculated for the most common types of telephone sets and battery supplies. Examples of the loop loss factors may be found in the Bell System Practices AB43 series.

In assessing the effect on transmission of a change in the loop facility, then, the major problem is to determine the effective loss with a fixed telephone set and a fixed transmitter battery supply. Factors for other sets and other batteries may then be deduced by comparison with known loop loss factors.

Since the effective loss of a circuit depends upon its total attenuation - frequency characteristic, the calculation of effective loss is not straightforward. Coolidge and Gannett[2] have suggested that the effective

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[2] Transmission Aspects of Wire Communications - O.H. Coolidge and D.K. Gannett; Volume I, Chapter 6, Page 41.

insertion loss of a voice frequency telephone circuit is closely approximated by its true insertion loss at 1500 cps. This agrees well with the equivalent recommendation of the C.C.I.T.T.[3] Throughout this report this criterion will be used as the basis on which suggested modifications to the line facility are judged.

Several other factors must be considered in assessing the suitability of modifications to a subscriber loop facility. Those of major importance are:

(a) The performance of the loop must be stable with time and weather,

(b) the sidetone performance of the telephone set must not be degraded appreciably,

(c) the echo return loss and singing margin must satisfy the requirements of the toll network.

Open wire circuits do change in transmission performance as the weather changes. The magnitude of these changes is known for existing types of facilities. For suggested modifications to the facility the effect of changes in performance will be judged by comparison with the known changes for standard facilities. Similarly the effect of circuit impedances on the sidetone performance of telephone sets will be judged by comparison with existing facilities.

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[3] Annex 4 of draft text for Section 5 - Transmission, of the Volume to be published under Question 8/XI; dated 16 January 1963.

The echo return loss and singing margin are functions of the input impedance of the subscriber loop at the central office in comparison to the nominal office impedance. Echo return loss is defined as the average return loss over the frequency band 500 - 2500 cps. In the Bell System the objective is defined as a normal probability function with an average of 11 db and standard deviation of 3 db. The singing margin is defined as the minimum value of return loss in the frequency band 200 - 3200 cps. The Bell System objective is again a normal probability function, whose average is 6 db and standard deviation 2 db.

## 3. The Transmission Problem For Long Rural Loops

As shown in the introduction to this report the rural telephone plant has been constructed to provide satisfactory performance on a manual switching basis. The introduction of dial service requires that the switching functions be concentrated in larger, more centralized offices. Thus the introduction of dial service lengthens the subscriber loops and increases their transmission loss. In this section the type of line facility commonly used will be examined to determine the amount of transmission improvement which is necessary to provide adequate performance over the lengthened loops.

The type of facility most commonly used for long rural lines in the Prairie Provinces is composed essentially of .109 inch diameter steel open wire with entrance cables usually of 22, 24 or 26 gauge. The maximum range for loop dial operation is restricted by the office supervision limit to 1300 ohms loop resistance. This corresponds to a maximum range of about

17 miles for the steel wire facility.

Simplex dialling allows the office supervision range to extend to 5000 ohms, or a maximum distance of nearly 70 miles. Transmission limitations, however, restrict the maximum loop length for this type of operation to about 22 miles. Thus the additional supervisory range permitting by simplex dialling cannot be exploited because of transmission requirements.

A large proportion of the long rural loops are in the range of 30 - 50 miles in length. The effective loss of .109 steel wire is .365 db per mile hence transmission improvements of the order of 3 to 10 db are required.

In addition to this overall transmission improvement it is also desirable to improve the frequency - attenuation characteristic of the loop facility. Mr. R. G. Hinderliter[4] has shown that the maximum slope across the voice band for existing subscriber loops is 12 db, and that only 10% of existing loops exhibit slopes greater than 9 db. The insertion loss of fifty miles of .109 inch steel wire is 10 db at 300 cps and 34 db at 3000 cps, giving a slope of 24 db. Thus a suitable solution to the long rural loop transmission problem must provide for a net decrease in effective transmission loss of 3 to 10 db, and an improvement in the frequency - attenuation characteristic of the line.

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[4] Transmission Characteristics of Bell System Subscriber Loop Plant R. G. Hinderliter; A.I.E.E. Conference Paper 62-1198 dated 11 April 1962.

The transmission performance of long rural loops can be improved either by converting the facility to lower loss conductors, or by installing subscriber carrier channels. These techniques are costly in relation to the improvement gained by the telephone company. Hence a more economical method of achieving transmission improvement is required.

Voice frequency repeaters offer one method of improving transmission efficiency. It will be shown, however, that the realizable gain is not sufficient to meet the needs of the long rural loop. Additional improvement can be achieved by inductive loading of the iron wire. The combined improvements of loading and repeaters is sufficient to satisfy the transmission objective.

# CHAPTER II

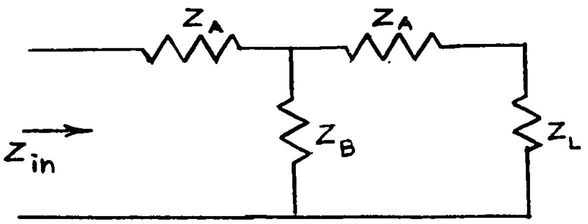
# APPLICATION OF REPEATERS TO LONG RURAL LOOPS

## 1. Introduction

The most obvious method of achieving transmission improvement is through the use of voice frequency repeaters. Such repeaters may be mounted in the office or at convenient points along the loop facility. Office mounted repeaters are attractive from practical considerations since they are easily installed and maintained, they are protected from the weather, and power supplies are readily available. From a transmission viewpoint they are less desirable since they must achieve all necessary gain in one step and since they are inserted at a point of minimum signal to noise ratio in one direction of transmission. The cost of providing suitable pole mounted repeaters for this type of service is presently prohibitive. Therefore despite their disadvantages only the office mounted repeater is of practical value.

Limitations on the achievable gain of the repeater are imposed by considerations of signal to noise ratios, stability margins and return loss requirements. The cost of improving the noise performance of a loop is difficult to assess. However it will be shown that stability margins demand low operating gains for the service envisaged hence improved noise performance is seldom required. The limitations of stability and return loss are imposed by the expected variations of impedance of the repeatered circuit and of any circuits with which it may be connected.

For the subscriber loop itself an estimate of the variations in input impedance may be obtained from a consideration of the T-network equivalent of a loop. Assuming rather ideal conditions in which only one facility type is involved the equivalent network is as shown in Figure 1.



$Z_L$ = Terminating Impedance

$Z_A$ = $Z_0 \tanh \gamma l/_2$

$Z_B$ = $Z_0 \sinh \gamma l$

$Z_0$ = Characteristic Impedance

$\gamma$ = Propagation Constant

l = Facility Length

FIGURE 1

EQUIVALENT T NETWORK OF SIMPLE LINE

The input impedance of this circuit is given by:

$$Z_{in} = Z_0 \left( \frac{\sinh \gamma l + \frac{Z_L}{Z_0} \cosh \gamma l}{\frac{Z_L}{Z_0} \sinh \gamma l + \cosh \gamma l} \right) \qquad (1)$$

$Z_{in}$ changes with variations in $Z_0$, $\gamma$ and $Z_L$. For .109 inch steel wire the variation in $Z_0$ between dry and wet weather conditions is about 3% and in $\gamma$ about 8%. The value of $Z_L$ depends upon the number of telephones actually off hook at any instant. Normally either 0, 1 or 2 telephones are of hook but the number can, of course, be higher. For the lengths of .109 steel wire being considered rapid changes of impedance magnitude of the order of ± 10% may be expected, with additional fairly long term changes of the same order of magnitude. Thus, as an approximate measure of stability, it is essential that any repeater used be stable with line impedance variations of the order of ± 20%.

On the office side of the repeater the nominal impedance level is 900 ohms plus 2.16 ufd. For revertive calls, however the impedance is very high. For locally connected calls the repeater must be stable when connected to other loop facilities either repeatered or non-repeatered. For toll calls the return loss and singing margin requirements as specified in Chapter I must be satisfied.

In addition to these requirements it is essential that the repeater permit office interconnecting functions to be accomplished. This implies that the repeater must provide means to transmit the dc loop currents, dial pulses and ringing currents in addition to the speech signals.

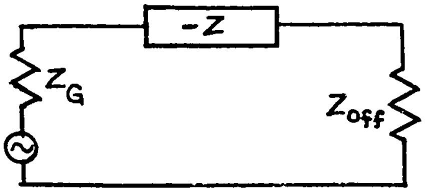
Two general types of repeaters are available for this type of service, namely negative impedance and hybrid repeaters. In this Chapter the limitations on the use of each type will be developed.

## 2. Office Mounted Negative Impedance Repeaters

Of the two generic repeater types those employing negative impedance elements are attractive in the subscriber loop field because they may be designed to permit direct transmission of dc loop current, dial pulses and ringing voltages.

Stability criteria of different configurations of the various type of negative impedance repeaters are discussed in a paper by A. I. Larky[5]. In this paper it is shown that a non-ideal converter may be made to appear as an ideal one by adopting specified circuit configurations. It will be convenient, then, to consider an ideal converter in studying stability and impedance considerations to derive approximate gain limitations of these devices.

A series type negative impedance repeater may be represented by the equivalent circuit of Figure 2.



$Z_G$ = Input impedance of subs. loop

$-Z$ = Effective impedance of Repeater

$Z_{off}$ = Office Impedance

FIGURE 2

REPRESENTATIVE OF IDEAL SERIES NEGATIVE IMPEDANCE REPEATERS

The gain of the repeater in this circuit is:

$$20 \log \left| \frac{Z_G + Z_{off}}{Z_G + Z_{off} - Z} \right| \qquad (2)$$

The return loss to $Z_{off}$ is:

$$20 \log \left| \frac{Z_{off} + Z_G - Z}{Z_{off} - Z_G + Z} \right| \qquad (3)$$

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[5] Negative Impedance Converter Design — A. I. Larkey. Stanford Electronics Laboratories Technical Report No. 30 dated October 30, 1956.

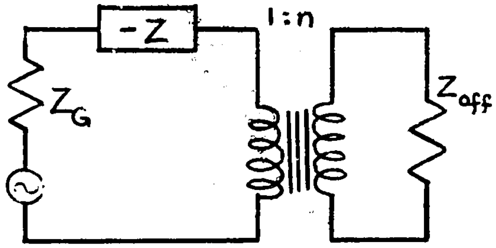
and the repeater is stable if $|Z_{off} + Z_G| > |-Z|$ at all frequencies.

The operating limitations of this circuit are depicted in Figure 3 in which, for illustrative purposes the 1000 cps parameters of a long .109 steel wire line and of the office have been used. The limiting condition for assessing performance has been taken as a reduction of 20% in line input impedance as outlined in Section 1 of this Chapter.

Figure 3 shows that to ensure stability for two similar circuits connected in tandem the maximum permissive gain is about 4.5 db. The 1% minimum of the acceptable return loss is also reached at the same figure. Since some margin must exist for manufacturing tolerances and for the practical impossibility of synthesizing precisely the optimum form of negative impedance desired across the frequency band the practical maximum of achievable gain is about 3.5 to 4.0 db. As pointed out in Chapter I, some form of frequency dependence is necessary to achieve the desired degree of transmission improvement. The average improvement across the voice band will, therefore, be somewhat less than the maximum achievable gain.

It is apparent that a simple series only negative impedance repeater, terminal mounted cannot provide all of the required transmission improvement for the type of long rural subscriber line being considered.

In an unpublished memorandum Mr. E. S. Kelsey has suggested a modification to this repeater which alleviates the return loss problem and the problem of instability when two circuits are connected in tandem. The modification consists of inserting a transformer with a turns ratio such that the impedance of the repeatered line is raised to match the office impedance. The equivalent circuit is illustrated in Figure 4 and its operating limitations are shown in Figure 5.



$Z_G$ = Input Impedance of Subs. Loop
$-Z$ = Effective Impedance of Repeater
$Z_{off}$ = Office Impedance
1:n = Transformer Turns Ratio

FIGURE 4

EQUIVALENT CIRCUIT OF MODIFIED IDEAL SERIES
NEGATIVE IMPEDANCE REPEATER

The return loss for this circuit is:

$$\text{R.L.} = 20 \log \left| \frac{Z_{off} + n^2(Z_G - Z)}{Z_{off} - n^2(Z_G - Z)} \right| \qquad (4)$$

which is infinite if,

$$n^2 = \frac{Z_{off}}{Z_G - Z} \qquad (5)$$

The gain of the repeater is given by

$$G_n(db) = 20 \log \left| \frac{n(Z_{off} + Z_G)}{Z_{off} + n^2(Z_G - Z)} \right| = 20 \log \left| \frac{n(Z_{off} + Z_G)}{2\, Z_{off}} \right| \text{ if (5) holds} \qquad (6)$$

In practice $Z_{off}$ and $Z_G$ vary with frequency, hence for any desired value of gain $-Z$ must also vary with frequency. To achieve optimum return loss at all frequencies n must also, in general, vary with frequency. Practically then, it is not possible to achieve infinite return losses, however the return loss can be held to much higher values than for the repeater of Figure 2.

The operating limitations for this repeater are depicted in Figure 5 where again for illustrative purposes the operating conditions are taken as those existing on a .109 steel wire loop at 1000 cps. As in the previous example stability of the repeater has been shown with the input impedance of the line reduced by 20%. Again the characteristics indicate that the maximum achievable gain is of the order of 4.5 db, and the net effective gain will be somewhat less than this value.

Shunt type negative impedance repeaters may also be used for this purpose. Since shunt and series repeaters are duals[6] the same type of analysis would apply to either type. For the shunt repeater stability becomes critical when load conductances are low, thus the same changes in operating characteristics apply to the shunt repeater when line impedances are increased by 20% as apply to the series repeater when impedances are decreased 20%. In addition the shunt

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[6] Transmission Aspects of Wire Communications -- O. H. Coolidge and D. K. Gannett, Volume II, Chapter 8, Section 8.7.

repeater would be even more unstable during idle conditions or when a revertive call is in process, hence it is less suitable for the proposed application than is a series repeater.

Finally a combination series-shunt repeater may be employed. The permissive gain may be increased by 3 db by dividing the gain equally between the series and shunt elements. Because of the idle circuit and revertive call conditions, however, the gain of the shunt section is more restricted than that of the series element, hence the realizable gain is somewhat less than 3 db more than for the series only repeater.

It is apparent then, that office mounted negative impedance repeaters alone cannot provide the desired degree of transmission improvement. It must be emphasized, however, that the above analysis applies only to office mounted repeaters and was forced by the practical problems associated with externally mounted repeaters of present design. If these practical problems can be solved by some future techniques the application of pole mounted repeaters offers a very attractive solution to the problem.

### 3. Office Mounted Hybrid Type Repeaters

A hybrid type repeater is of the form shown in Figure 6. For the present purpose it is attractive since the office side of the repeater is isolated from the line and can, therefore, be well matched for interconnection to other circuits regardless of changes in the input impedance of the subscriber loop. Because of its configuration it is necessary to provide an auxilliary path for transmission of loop currents, dial pulses and ringing currents. This auxilliary equipment adds to the cost of the repeater, hence it is economically less attractive than negative impedance types for subscriber loop application.

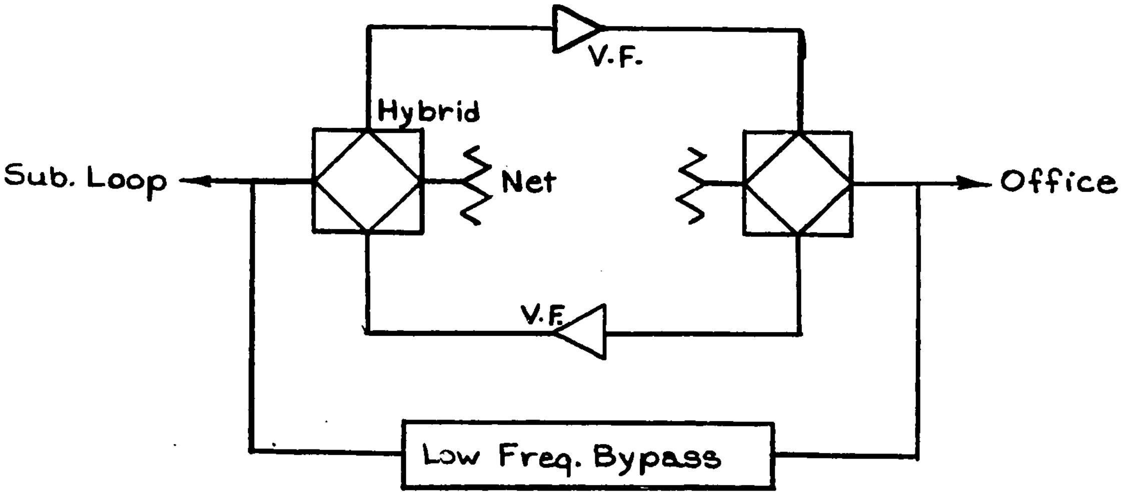
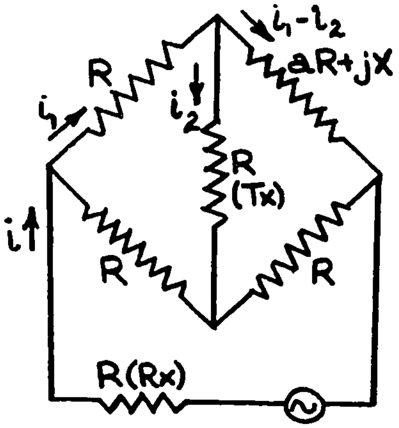


FIGURE 6

HYBRID TYPE REPEATER

The stability of this repeater is a function of the balance between line and hybrid networks. The effect of unbalances may be studied by considering a resistive hybrid network in the form shown in Figure 7. Such a network is balanced only for resistive terminations, a condition which does not apply when used for subscriber loop service. An analysis based on the resistive net is quite general, however, if it is considered that the effect of all unbalances in the circuit are transformed into the unbalance between line and balancing network.



$\frac{aR + jX}{R}$ = Effective unbalance line to Network

Tx = Transmitting Amplifier

Rx = Receiving Amplifier

FIGURE 7

RESISTANCE HYBRID

From this circuit it follows that:

(a) The fraction of current from line which is applied to the transmitting amplifier $= \frac{R}{2R} = \frac{1}{2}$ (7)

(b) The fraction of output current from receiving amplifier fed to the line $= \frac{i_1-i_2}{i} = \frac{4R}{5R + 3aR + j2X}$ (8)

(c) The fraction of output current from receiving amplifier fed to the transmitting amplifier $= \frac{i_2}{i} = \frac{aR-R+jX}{5R + 3aR + jX}$ (9)

In a working circuit the distribution of currents is as shown in Figure 8.

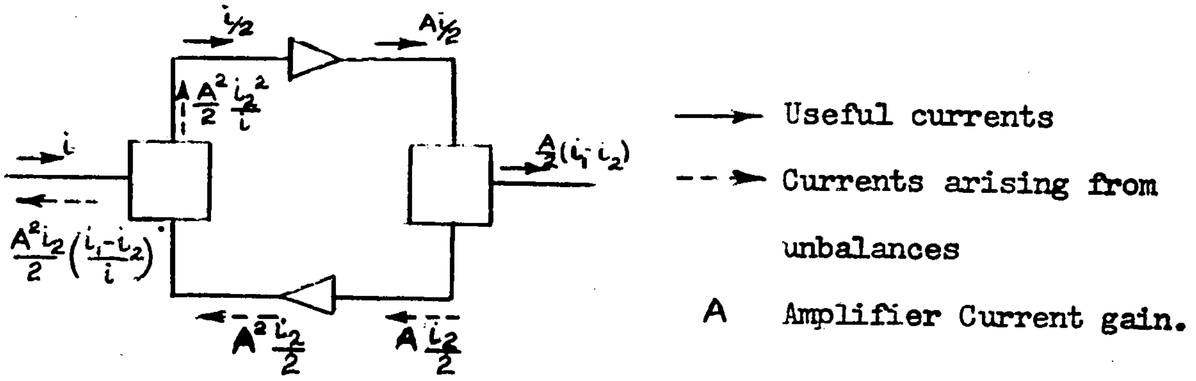


FIGURE 8

CURRENT DISTRIBUTION IN HYBRID REPEATER

Thus the circuit becomes unstable when

$$\frac{A^2}{2}\,\frac{i_2^2}{i} = \frac{i}{2} \text{ or } A_{max} = \frac{i}{i_2} \qquad (10)$$

The minimum amplifier gain for zero loss is

$$A_0 = \frac{2i}{i_1 - i_2} \qquad (11)$$

Therefore the maximum net gain,

$$B_{max} = \frac{i_1 - i_2}{2i_2} = \frac{2R}{aR-R+jX} \qquad (12)$$

This function is plotted in Figure 9 for values of X which yield mismatch phase angles of 0°, 10° and 20°.

Severe distortion is created if a repeater of this type is operated at or close to its point of instability. In practice the gain is reduced to provide a "singing margin" of 6-10 db. The maximum useable gain is also plotted on Figure 9 for an average stability margin of 8 db.

A worse condition of unbalance exists when the circuit is idle or when a revertive call is in progress. In either case the office hybrid is terminated effectively in an open circuit. The maximum useable gain for a resistive unbalance of 20% with no phase discrepancy is reduced to approximately 1 db under this condition. It is obvious then that a dummy load or "idle line termination" must be applied to the office hybrid whenever the circuit is idle or when a revertive call is in progress.

Even with the idle line termination it is unlikely that stable, undistorted gains higher than 5 db can be realized on iron wire subscriber loops using a hybrid repeater. Again since some frequency dependence of the gain is desired the average effective gain will be somewhat lower than this figure.

## 4. Conclusions

Of the available types of voice frequency repeaters the series negative impedance repeater is the most attractive economically. When office mounted on long rural subscriber loops the maximum useable stable gain for this type of repeater is approximately 4 db. Other forms of negative impedance devices offer little hope of improved performance because of the wide impedance variations encountered in this type of service.

Hybrid type repeaters can give slightly higher stable gain performance at the expense of added equipment complexity. With this repeater the maximum useable gain is of the order of 5 to 6 db which is still insufficient for the desired transmission improvement.

It is apparent, therefore that terminal mounted repeaters alone cannot provide all of the desired transmission improvement. A suitable solution must be sought in some other technique which alone, or in conjunction with repeaters, will permit higher degrees of stable gain to be achieved.

# CHAPTER III

# INDUCTIVE LOADING PATTERNS FOR .109 STEEL WIRE

## 1. Introduction

In Chapter II it was shown that office mounted repeaters alone could not provide all of the transmission improvement required for long rural subscriber loops. The next approach, then, is to examine the primary constants of the loop facility to determine if they can be altered in such a manner as to decrease the insertion loss.

The process of adding impedances at appropriate intervals to alter the characteristics of a line is called loading. Generally any or all of the primary constants may be altered by the addition of continuous or discrete, series or shunt elements. A wide range of insertion losses and line impedances can be realized. An excellent description of this generalized loading concept is given by Coolidge and Gannett in <u>Transmission Aspects of Wire Communications</u>, Volume II, Chapter 8.

A decrease in the insertion loss of any practical line facility in the voice frequency range can be realized by decreasing resistance (R), Conductance (G) or Capacitance (C), or by increasing Inductance (L). For a given line conductor and physical configuration R, C and G may be decreased only by the insertion of negative impedance elements.

The inductance, however, may be increased by the insertion of passive elements at appropriate intervals.

The insertion of negative impedances at appropriate intervals is effectively a generalized concept of line mounted negative impedance repeaters. This approach is very attractive in theory, but practical considerations preclude its use. Thus any transmission improvement which can be achieved by loading must be realized by inductive loading.

A review of the evolution of existing inductive loading patterns is contained in the Bell System Technical Journal.[7] In this Chapter the effects of inductive loading applied to .109 inch diameter steel wire lines will be examined to determine the degree of transmission improvement which can be achieved. This examination will be used to specify a recommended loading pattern for long rural loops.

## 2. The Effects of Inductive Loading

The secondary constants of a transmission line are the characteristic impedance, $Z_o$, and the propagation constant, $\gamma$. They are related to the primary line constants by the following expressions:

$$Z_o = \left( \frac{R + jwL}{G + jwC} \right)^{1/2} \qquad (13)$$

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[7] The Evolution of Inductive Loading for Bell System Telephone Facilities — Thomas Shaw; Bell System Technical Journal Volume 30, 1951, pages 149 - 203.

$$\gamma = \alpha + j\beta = [(R + jwL)(G + jwC)]^{1/2} \qquad (14)$$

in which $\alpha$ is the attenuation constant and $\beta$ is the phase constant. In general both secondary constants are frequency dependent.

$Z_o$ can be made purely resistive, and independent of frequency if L is altered to the value at which

$$\frac{wL}{R} = \frac{wC}{G} \quad \text{or} \quad L = \frac{CR}{G} \qquad (15)$$

This relationship defines a distortionless condition for which

(a) $Z_o = \sqrt{\frac{R}{G}} = \sqrt{\frac{L}{C}}$, a pure resistance independent of frequency,

(b) $\alpha = \sqrt{RG}$, a constant independent of frequency,

(c) $v = \frac{\omega}{\beta} = \frac{1}{C}\sqrt{\frac{G}{R}}$, a constant independent of frequency,

where $v$ is the velocity of propagation.

The values of the propagation characteristics of .109 steel wire lines are shown in Table I. In this table L has been selected to satisfy the distortionless condition at a frequency of 1000 cps for dry weather conditions.

| CHARACTERISTIC | Non Loaded Line | | Loaded Line | |
|---|---|---|---|---|
| | Dry | Wet | Dry | Wet |
| L - MH. Per mile | 10.3 | 10.5 | 7030 | 7030 |
| $Z_o$ - OHMS | 1279-j629 | 1274-j578 | 29,100 | 28,500 + j 248 |
| - DB./MILE | .289 | .313 | .025 | .420 |
| - MILES/SEC. | 93,500 | 92,000 | 4150 | 4030 |

TABLE 1

CHARACTERISTICS OF .109 STEEL WIRE LINE LOADED TO DISTORTIONLESS CONDITION FOR DRY WEATHER. FREQUENCY 1000 C.P.S.

The table illustrates that a decrease in the attenuation constant of a loop facility as a result of loading is accompanied by an increase in line impedance, a decrease in velocity of propagation, and an increase in the difference between wet and dry weather attenuation characteristics. The serious problem is the increased differential between dry and wet weather losses. The choice of loading weight must be a compromise between the degree of transmission desired, and the difference between wet and dry weather performance which can be tolerated.

A second compromise is required in the choice of loading pattern. A loaded line containing no discontinuities can be realized only if the inductance is added continuously. This implies a change in the basic characteristic of the line conductor and cannot be applied to existing lines. It is, therefore, necessary to add the loading inductance at discrete intervals.

The discontinuity of a loading inductor causes the line to resemble a series of low pass filter networks. In each network the series element is the total inductance of a loading section and the shunt element is the line capacitance. Lumped loading of a line thus introduces a cut-off frequency whose value is cycles per second is given by:

$$f_c = \frac{1}{\pi \sqrt{L_s C_s}} \qquad (16)$$

where $L_s$ = inductance per loading section, and

$C_s$ = capacitance per loading section.

Since both L and C increase with increased load coil spacing the choice of cut-off frequency limits the selection of load coil size and loading section length.

Thus the effects of loading an open wire line may be summarized as follows.

(a) Loading decreases the attenuation of a line and makes it more nearly constant with frequency;

(b) Loading increases the line impedance, makes it more nearly resistive and more nearly constant with frequency;

(c) Loading decreases the velocity of propagation and makes it more nearly constant with frequency;

(d) Loading increases the difference in attenuation constant between dry and wet weather conditions; and

(e) Lumped loading introduces a cut-off frequency above which the attenuation is very high.

A suitable loading pattern, therefore, is one whose loading weight provides a reasonable degree of transmission improvement with acceptable changes in other transmission characteristics. This loading weight must be applied to the line in a pattern in which the cut-off frequency imposes no appreciable degradation in transmission quality.

## 3. Choice of Loading Weight

In Table 1 the transmission characteristics of a .109 steel wire line loaded to the distortionless condition were presented. Obviously such heavy loading is neither necessary nor desirable.

The choice of a more suitable loading weight is a compromise between the degree of transmission improvement, the permissive increase in characteristic impedance and the permissive difference between dry and wet weather transmission characteristics. These characteristics for more reasonable loading weights are illustrated in Figure 10.

The difference between wet and dry weather losses of a fifty mile length of .109 steel wire is 1.0 db. A reasonable design criterion for the loaded line is that this difference should not increase by more than 1.0 db. This limit is reached at an inductance value of 80 millihenries per mile. Hence this value can be considered an upper limit on the permissive loading weight.

A second limit is assigned by the permissive increase in line impedance. This increase affects the return loss to the switching office and the sidetone balance of the telephone set. Both may be compensated to some degree, if necessary, by the use of matching transformers. At the office one transformer only is required. If impedance matching at the telephone is necessary, however as many as fifteen transformers will be necessary for party line service. It is not desirable, therefore, to resort to impedance matching at the telephone. The effect of increased line impedance on the sidetone balance of a telephone is thus a controlling factor in the maximum useable loading weight.

The sidetone suppression of standard telephone sets on working loops varies over a 10 db range.[8] No appreciable change in the behaviour of the telephone set should occur, then, if the decrease in sidetone suppression as a result of loading is restricted to say 3 db. The relative sidetone levels for differring line impedances are plotted in Figure 11. The increase in sidetone suppression will be less than 3 db if the line inductance does not exceed 50 millihenries per mile. This then represents the maximum useable value of inductance without recourse to matching transformers at the telephone set.

These restrictions establish the maximum loading weights which may be applied to .109 steel wire lines. It remains to determine if sufficient transmission improvement can be realized within these limitations.

The wet and dry weather losses of .109 steel wire at 1000 cps are .297 and .313 db per mile respectively. The corresponding figures for a line loaded to 50 millihenries per mile are .152 and .185 db per mile. The net transmission improvement for a fifty mile length of line is therefore 7.2 db in dry weather and 6.4 db in wet weather. Although these values do not achieve the total desired range of improvement, they are considerably higher than the gains which may be realized by the use of office mounted repeaters. Also the additional improvement necessary to achieve the maximum desired gain of 10 db is within the capabilities of office mounted repeaters.

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[8] An Improved Telephone Set — A. H. Inglis and W. L. Tuffnell. Bell System Technical Journal Volume 30, 1951, pages 239 - 270.

Thus the maximum value of line inductance which may be used safely on .109 steel wire is 50 millihenries per mile. This corresponds to a maximum loading weight of 40 millihenries per mile since the self inductance of the facility is 10 millihenries per mile. The transmission improvement which can be expected from this loading weight approaches 7.0 db at 1000 cps for a fifty mile loop.

### 4. Choice of Loading Pattern

The choice of loading pattern is determined by the lowest permissive cut-off frequency. The highest frequency of concern for telephone transmission is about 3200 cps. The attenuation of a loaded line rises rather steeply at frequencies higher than 0.8 times the cut-off frequency, therefore the minimum acceptable cut-off frequency is 4000 cps.

The capacitance of an open wire circuit changes somewhat with weather conditions. As an example the capacitance of .109 steel wire is 4% higher in wet weather than in dry weather. The increase for sleet conditions is probably even greater. Thus the design cut-off frequency for dry weather conditions should be approximately 4500 cps to ensure that it is at least 4000 cps under adverse weather conditions.

From equation (16), for a cut-off frequency of 4500 cps,

$$L_s C_s = \frac{1}{\pi^2 f_c^2} = 5.00 \times 10^{-9}$$

The inductance per load coil section is the inductance of the coil plus the self inductance of the line. The capacity per section is the self capacitance of the line. Thus if $L_L$ is the inductance of the load coil section, and S is the maximum length of a section in miles:

$$L_s = LS + L_L \quad \text{and} \quad C_s = CS, \text{ hence}$$

$$CS(LS + L_L) = 5.00 \times 10^{-9} \tag{17}$$

For 88 mh coils, which are the most common standard type, the maximum spacing is 4.6 miles which corresponds to a total inductance of 30 mh/mile. The next larger standard coil is 176 mh. The maximum coil spacing with this coil is 2.9 miles corresponding to an inductance of 71 mh/mile. This exceeds the permissive loading weight, hence the largest standard coil which can be used is 88 mh.

The maximum permissive loading weight is 40 mh/mile. Using 88 mh. coils the minimum loading section is 2.2 miles, and the maximum is 4.6 miles. To determine the optimum spacing the insertion loss of thirty miles of .109 steel wire was calculated for loading sections of 1.5, 3.0 and 5.0 miles. The results are illustrated in Figure 12.

The performance of the line when loaded 88 mh/1.5 miles differs little from that when loaded 88 mh/3.0 miles. There will be an even smaller difference for the minimum permissive spacing of 2.2 miles. Thus virtually all of the realizeable improvement is obtained for a load coil spacing of 3.0 miles. This, then was adopted as the standard pattern. It ensures that the objectives for cut-off frequency, increase in line impedance and increased loss in wet weather are fully satisfied.

## 5. Transmission Characteristics of .109 Steel Wire Loaded 88 mh/3 miles

Following the normal practice in the telephone industry the characteristics of loaded steel wire will be presented in two forms.

(a) The facility, or long line characteristics; and

(b) the subscriber loop characteristics.

The facility characteristics are those which are applicable when the facility is terminated in its characteristic impedance. They are, therefore, the basic transmission properties of the line. These properties are described as:

(a) The nominal cut-off frequency;

(b) the propagation constant;

(c) the mid-section impedance; and

(d) the iterative impedance for various end sections.

The subscriber loop characteristics are those which are applicable when the facility is terminated in the impedance of a telephone set. These are the Loop Loss Factors used in the design of sbuscriber loops. The particular factors are:

(a) The effective insertion loss of the facility for various lengths of loop;

(b) the return loss at the switching office.

(c) the loop loss factors, or the loop loading gain factors; and

(d) the mismatch loss at junctions of dissimilar facilities.

## 5.1 Facility Characteristics

### (a) Nominal Cut-Off Frequency

The nominal cut-off frequency of a loaded facility is given by:

$$f_{(c)} = \frac{1}{\pi\sqrt{L_s C_s}} \qquad (16)$$

For .109 steel wire the capacitance per three miles load section is .0252 $\mu$f in dry weather and .0261 $\mu$f in wet weather. The exact value of the self inductance of the line at the cut-off frequency is not known since the self inductance varies with frequency. If a load coil spacing of 4.6 miles is used, the cut-off frequency is 4500 cps (see section 4), therefore with a three mile spacing the cut-off frequency is about 6000 cps. At this frequency the self inductance of the line is very nearly 7 mh. per mile or 21 mh. per loading section. The total inductance per load coil section, using an 88 mh. coil, is 109 mh., and the nominal cut-off frequencies are:

Dry weather - 6075 cps.
Wet weather - 5967 cps.

### (b) Propagation Constant

The propagation constant, at low frequencies, may be calculated from the expression:

$$\gamma = [(R + jwL)(G + jwC)]^{1/2} \qquad (14)$$

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The propagation constant, at low frequencies, may be calculated from the expression:

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For a loaded line this expression is accurate to at least 35% of the cut-off frequency, is reasonably accurate to about 70% of the cut-off frequency but departs rapidly from the true value for higher frequencies. In the present investigation the propagation constant was calculated at frequencies up to 3400 cps using formula (14). The attenuation results were compared with those obtained by computer simulation of 100 and 200 mile lengths of the line. The results agreed within 1.6% at 3400 cps.

The values of the propagation constant, in the frequency range 200 - 3400 cps for wet and dry weather conditions, are listed in Table 2.

### (c) Mid-Section Impedance

The mid-section impedance was calculated by computer simulation of a 100 mile length of the facility. These values were spot checked against those of a 200 mile length.at frequencies of 300, 1000 and 3000 cps. The maximum discrepancy, at 300 cps was 1.8% in impedance magnitude and 1.8° in phase angle. The results, based on the 100 mile simulation, are listed in Table 2.

### (d) Interative Impedance at Various End Sections

The variation of impedance with length of end section for various frequencies is illustrated in Figure 13. These curves were also obtained by computer simulation of a 100

TABLE 2

SECONDARY CONSTANTS OF .109 STEEL WIRE, 12" SPACING

LOADED 88 MH PER 3.0 MILES

| Freq. Cyc. Sec. | Propagation Constant - Per Mile | | | | | | Mid Section Impedance | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Dry Weather | | | Wet Weather | | | r ohms | x ohms (Neg) | z ohms | Angle Degrees (Neg) |
| | Attenuation | | Phase Shift | Attenuation | | Phase Shift | | | | |
| | Nepers | db | Radians | Nepers | db | Radians | | | | |
| 200 | .0148 | .129 | .0280 | .0182 | .158 | .023 | 2406 | 966 | 2591 | 21.9 |
| 400 | .0163 | .141 | .0543 | .0200 | .173 | .046 | 2345 | 626 | 2427 | 15.0 |
| 600 | .0176 | .152 | .0712 | .0218 | .189 | .070 | 2245 | 501 | 2300 | 12.6 |
| 800 | .0188 | .163 | .0953 | .0228 | .197 | .094 | 2236 | 421 | 2275 | 10.7 |
| 1000 | .0200 | .173 | .1190 | .0239 | .206 | .1195 | 2232 | 362 | 2262 | 9.2 |
| 1200 | .0209 | .181 | .1400 | .0246 | .213 | .140 | 2235 | 318 | 2258 | 8.2 |
| 1400 | .0221 | .192 | .1608 | .0255 | .221 | .162 | 2242 | 280 | 2259 | 7.1 |
| 1600 | .0232 | .201 | .1821 | .0261 | .226 | .187 | 2246 | 251 | 2260 | 6.4 |
| 1800 | .0243 | .211 | .2047 | .0266 | .231 | .213 | 2250 | 238 | 2263 | 6.0 |
| 2000 | .0254 | .220 | .2279 | .0272 | .236 | .231 | 2254 | 228 | 2266 | 5.8 |
| 2200 | .0266 | .231 | .2498 | .0281 | .244 | .257 | 2255 | 222 | 2266 | 5.6 |
| 2400 | .0277 | .240 | .2716 | .0299 | .258 | .274 | 2256 | 215 | 2266 | 5.4 |
| 2600 | .0289 | .250 | .2940 | .0316 | .274 | .293 | 2269 | 210 | 2279 | 5.3 |
| 2800 | .0299 | .259 | .3151 | .0339 | .293 | .315 | 2298 | 205 | 2306 | 5.1 |
| 3000 | .0309 | .266 | .3354 | .0361 | .313 | .338 | 2351 | 204 | 2360 | 4.9 |
| 3400 | .0331 | .280 | .377 | .0424 | .366 | .387 | 2440 | 202 | 2448 | 4.7 |

**Nominal Cut-off Frequency:** dry 6075 cps.
wet 5967 cps.

mile length of facility.

It is obvious that the iterative impedance of the loaded facility is much greater than that of the central office, or of the entrance cables to which it may be joined. The shape of the impedance curves is, however, very similar to those of loaded cable. This suggests that a good impedance match might be obtained by impedance transformation.

Generally the steel wire facility will be joined to an entrance cable. If the impedance of the open wire can be transformed to a value which resembles that of loaded cable the junction loss will be minimized, and the advantages of loading can be extended to the entrance cable. A suitable transformation ratio is 2.0:1 which provides an optimum mid-band match for 19, 22 or 24 gauge entrance cables loaded with an H88 pattern. The transformed impedance characteristics are then one-half of the values shown in Figure 13 and may be compared with those for typical entrance cables as listed in Bell System Practices AB 42.265.

## 5.2 Subscriber Loop Characteristics

### (a) Insertion Loss

The formula for the calculation of insertion loss, including the effect of the transformation ratio is developed in Appendix 2.

In Figure 14 is shown a comparison of the insertion loss-frequency characteristic for 30 miles of loaded and non-loaded steel wire, when terminated in a standard type of rural telephone set. It is interesting to note that:

(i) the mid-band (1500 cps) insertion loss is reduced by loading from 10.7 to 7.2 db, a gain of 3.5 db.

(ii) the attenuation slope across the voice band (300 - 3000 cps.) is reduced by loading from 6.9 to 3.0 db.

Similarly in Figure 15 the 1000 cps and 1500 cps insertion losses of non-loaded and loaded steel wire are compared for various lengths of line. The effective loop loss of non-loaded steel wire is .069 db/kilofoot or .364 db/mile, which agrees very closely with the computed 1500 cps insertion loss. The corresponding loss for the loaded facility is represented quite accurately as:

$$\text{Loss} = (.0405L + 1.5) \text{ db} \quad L \text{ in Kilofeet} \qquad (18)$$

$$\text{Loss} = (.214L + 1.5) \text{ db} \quad L \text{ in miles} \qquad (19)$$

in which L is the length of facility in appropriate units. At 50 miles the effective transmission improvement due to loading is 6.0 db.

## (b) Return Loss at Switching Office

In subscriber loop plant the line facility is not terminated in its characteristic impedance. The line impedance, as seen from the office, thus varies with the circuit length. No precise values for the general return loss can be given.

To obtain some concept of the values which might be achieved in practice, the return loss has been calculated for 30 mile lengths of loaded and non-loaded steel wire lines. These results are shown in Figure 16. The average values are:

| | Loaded | Non Loaded |
|---|---|---|
| Echo return loss | 12.9 | 10.7 |
| Singing margin | 8.0 db | 6.9 db |

Thus both the echo return loss and singing margin are somewhat improved as a result of loading.

(c) Loop Loss Factors

Loop loss factors for .109 steel wire non-loaded, local battery loops are listed in Bell System Practice AB 43.551. They comprise an effective insertion loss factor of .069 db per kilofoot and a constant factor of 3.3 or 4.4 db depending upon the office type. The corresponding factors for .109 steel wire, loaded 88 mh. per 3.0 miles, on local battery loops are:

(i) Insertion loss factor .0405 db per kilofoot;

(ii) constant factor 4.8 or 5.9 db dependent on office type.

Often it is convenient to calculate effective losses in terms of non-loaded facilities, then apply correction factors for loading coils. Correction factors for cable loading patterns are listed in Bell System Practice AB 43.519. They have the form

$$\text{Loading gain} = (AN - B) \text{ db} \qquad (20)$$

in which A is a loading gain factor per load coil

N is the number of load coils in the facility

B is a constant factor.

Factor B is 1.5 db for all H88 loading patterns. As shown in section 5.1 (b) the same factor applies to .109 steel wire when loaded.

Factor A is 1.1 db for 19 ga. cables loaded H88, and 1.5 db for 22, 24 or 26 ga. H88 loaded cables. The corresponding factor for .109 steel wire loaded 88 mh per 3.0 miles is the difference in effective insertion loss for a three mile length of loaded facility as compared to that of non-loaded wire. Thus the factor becomes $3(.364 - .214) = 0.45$ db.

Equation (19) may be generalized for loops of various types of facilities, provided that the loading pattern on cable sections is H88, and on open wire sections is 88 mh. per 3.0 miles. The general equation becomes:

$$\text{Loading Gain} = (\Sigma A_i N_i) - 1.5 \text{ db} \qquad (21)$$

in which $A_i$ is the loading gain factor per load coil for facility type i, and

$N_i$ is the number of load coils in facility type i.

The appropriate factors, for commonly encountered facilities, are shown in Table 3.

| Facility Type | | Factor A |
|---|---|---|
| Cable | 19 ga. | 1.1 db |
| | 22 ga. | 1.5 db |
| | 24 ga. | 1.5 db |
| | 26 ga. | 1.5 db |
| Open Wire | .109 steel wire | 0.45 db |
| | .104 cd. cu (40%) | 0.27 db |
| | .104 copper | 0.09 db |

TABLE 3

LOADING GAIN FACTORS FOR H88 LOADING PATTERN (CABLE) AND FOR 88 MH/3.0 MI. (OPEN WIRE)

Factors for .104 Cd. Cu. and .104 Copper lines have been included to cater for incidental lengths of these facilities in a loop basically consisting of .109 steel wire. Although the loading gain is small in these facilities it is essential that the load pattern be continuous through such incidental lengths to avoid a decrease in cut-off frequency.

### (d) Junction Mismatch Losses

Mismatch losses are those which result from the interconnection of two facility types of dissimilar impedance. In practice they are calculated in terms of the characteristic or iterative impedance of the line,[9] although it is realized that exchange loops are seldom sufficiently long to exhibit these impedances.

A junction mismatch current loss is the ratio of current which flows through the junction as compared to that which would flow if no changes in facility existed. Mathematically

$$\text{Junction Mismatch Loss (db)} = 20 \log \frac{Z_1+Z_2}{2\ Z_1} \qquad (22)$$

in which $Z_1$ and $Z_2$ are the impedances of the connected facilities.

In Table 4 is shown the losses for junctions of .109 steel wire loaded 88 mh. per three miles with other commonly encountered facility types:

| Facilities Joined | Mismatch Loss |
|---|---|
| .104 Copper to .109 steel | 0.4 db |
| .104 Cd. Cu. (40%) to .109 steel | 0.4 db |
| H88 loaded cable to .109 steel | 0.2 db |

TABLE 4

JUNCTION MISMATCH LOSSES FOR LOADED FACILITIES

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[9] Rural Electrification Administration, Telephone Engineering and Construction Manual, Section 422, Issue No. 4, August 1959.

In this table it has been assumed that:

(i) Incidental lengths of open wire other than .109 steel are loaded 88 mh/3.0 miles.

(ii) a matching transformer of ratio 2.0:1 is inserted at the open wire cable junction.

## 6. Conclusion

It has been shown that, at least in theory, inductive loading of .109 steel wire lines to a loading weight of 88 mh. per 3.0 miles is an acceptable method of improving the transmission performance of a long rural subscriber line. The effective gain due to loading may be as much as 6.0 db on a fifty mile loop. This gain is accompanied by a decrease in the attenuation slope across the transmission band.

The result of experiments performed to confirm this theoretical approach are contained in Chater IV.

# CHAPTER IV

# EXPERIMENTAL RESULTS

## 1. Introduction

Three sets of experiments have been conducted to verify the calculated performance of loaded lines, repeatered and non-repeatered. The first was a preliminary experiment on a single non-working loop, intended only to ensure that the anticipated performance improvement could be achieved in practice. In the second experiment two operating circuits were loaded and left in service to verify performance stability. Finally in the third experiment three additional operating circuits were loaded, two of which were equipped with office mounted repeaters. Again these circuits were left in service to test operating stability.

In all instances the improvement in performance agreed well with the calculated results. Subscriber reaction to the changes in working circuits was satisfactory. There has been no evidence of changes in operating characteristics over periods of up to nine months service, nor has any difficulty been experienced in interconnections to other circuits of the exchange and toll plant.

The results of these experiments will be presented in this Chapter, and will be compared with the results anticipated from the analysis of Chapter III.

## 2. Experiment I — Bancroft - Maynooth, Ontario

The facility used in this experiment was a very old iron wire line which was no longer in service. It was composed of 4800 feet of 19 ga. non-loaded cable, 14.15 miles of .109 iron wire and 500 feet of 26 ga. non-loaded cable.

Initial measurements of insertion and return loss were made on the non-loaded facility. These were repeated for loading patterns of 88 mh/3.0 miles and of 176 mh/1.5 miles. Finally the relative responses of two standard types of telephones were measured over the three facility types. The results of these measurements are described below.

### (a) Loading Patterns

In general a loaded circuit should terminate with a half-section at the switching office. A loading coil is required, then, 3000 feet from the office in the 19 ga. entrance cable. It was not possible to arrange for the insertion of this coil, hence it was placed at the end of the cable, i.e. the cable terminated in a 0.80 end section. Although this does not appreciably affect the facility insertion loss, it does alter the input impedance and hence the return loss.

At the open wire -19 ga. cable junction an autotransformer was installed for impedance matching of the loaded facility. The impedance transformation ratio was 2.0:1 for an open wire loading pattern of 88 mh/3.0 miles and 5.0:1 for a pattern of 176 mh/1.5 miles. No impedance matching was used at the subscriber terminal.

(b) **Insertion Loss**

The measured values of insertion loss for the three facility conditions are shown in Figure 17. Both source and load impedances were 900 ohms for these measurements.

Table 5 shows a comparison of the expected and measured values of insertion loss for the line non-loaded, and loaded 88 mh/3.0 miles. The correlation between measured and calculated results is very good, thus confirming the expected performance of this loading pattern.

| Circuit Condition ⟶ | Non Loaded | | 88 Mh/3.0 Mi. | |
|---|---|---|---|---|
| Insertion Loss | Calc. | Meas. | Calc. | Meas. |
| Effective (1500 cps) | 6.8 | 7.2 | 5.0 | 4.9 |
| 300 cps | 4.7 | 5.3 | 5.5 | 5.9 |
| 1000 cps | 5.8 | 5.6 | 4.6 | 4.5 |
| 2000 cps | 8.4 | 8.5 | 5.7 | 5.1 |
| 3000 cps | 10.8 | 11.1 | 6.6 | 6.9 |
| Effective Loading Gain | - | - | 1.8 | 2.3 |

TABLE 5

COMPARISON OF CALCULATED AND MEASURED LOSSES (DB)

EXPERIMENT 1

This high degree of correlation was not realized for the heavier loading pattern. The effective loss with this pattern is only 0.1 db less than that of the lighter loading pattern. At frequencies higher than 1500 cps the measured loss departs widely from expected values. The shape of the curve of Figure 15 suggests that the departures are caused by reflections at the subscriber terminal. These results, then, confirm the conclusion of Chapter III that it is not advisable to use loading patterns appreciably heavier than 88 mh/3.0 miles.

(c) Return Loss

Measured values of return loss for the three facility conditions are shown in Figure 18. The echo return loss for the non-loaded, lightly loaded and heavily loaded conditions are 6.2 db, 11.6 db and 7.2 db respectively. Similarly the singing margins are 4.1 db, 8.1 db and 1.8 db respectively.

The increased echo return loss and singing margin for the facility loaded 88 mh/3.0 miles confirms the expectation of Chapter III. The low singing margin for the heavily loaded facility again demonstrates that it is unsuited for subscriber loop service.

(d) Telephone Set Response

To ensure that the improvements in return loss were realized in actual improvements in the quality of the talking circuit the overall acoustic response was measured. It is difficult to make accurate repetitive measurements since the response of the telephone varies somewhat with time, battery supply conditions, and with the packing condition of the carbon granules in the microphone. To reduce these influences to a minimum the measurements were averaged over three frequency runs, then combined into an average effective figure for the frequency band 500 - 2500 cps. In this way it was found that the effective improvement in delivered audio power due to the 88 mh/3.0 mile loading pattern was 2.35 db. The average decrease in insertion loss over the same frequency band is 2.45 db. Thus it may be concluded that the improvement in insertion loss characteristic is translated into a corresponding improvement in speech quality.

### (d) Conclusions

The first experiment thus illustrated that:

(i) The expected improvement in circuit performance due to loading can be realized in practice.

(ii) The optimum loading pattern for steel open wire is approximately 88 mh/3.0 miles. There is little advantage in increasing the loading beyond this value.

(iii) For this loading pattern the transmission improvement is accurately represented by the formulae of Chapter III.

(iv) The echo return loss and singing margin of a steel wire circuit are improved as a result of this loading pattern.

## 3. Experiment II — Estevan, Saskatchewan

The lines used for experiment II were working circuits with ten to fifteen party line subscribers each. This is, of course, the condition which may be expected in practice.

Each subscriber, on this type of loop, is connected to the main facility by varying lengths of open wire or drop wire taps. These taps represent an impedance load on the circuit even if the terminating telephone is on hook. Thus the terminating impedance is not accurately known, and the insertion loss of the circuit cannot be calculated with the same accuracy as for the simple loop of Experiment I.

The lines actually used for the experiment were one party line serving ten subscribers in a small village and one rural line serving fifteen subscribers in a rather large farming district. The main facility of each circuit was the same, however the party line was a pole pair (18 inch spacing) while the rural circuit was a non-pole pair with standard 12 inch spacing.

Each facility included:

3600 feet 26 ga. non loaded cable
2052 feet 24 ga. non loaded cable
1029 feet 16 ga. urban wire
4.0 miles .104 cd. cu. (40%) open wire
23.0 miles .109 steel wire.

The calculated overall effective loss of this facility, including mismatch losses is 15.1 db.

One loading coil was inserted in each entrance cable pair 3600 feet from the central office. A matching autotransformer of impedance ratio 2.0:1 was installed at the open wire-cable junction, and seven load coils at three mile spacing inserted in the open wire. In each facility one load coil was installed in the Cd. Cu. wire.

The expected loading gain, as calculated from Equation 21 is 3.0 db. In addition the mismatch loss, which totals 2.6 db for the non-loaded facility, is reduced to 0.3 db by loading. The overall expected improvement therefore is 5.3 db. Thus the expected effective loss for the loaded line is 9.8 db.

Measured values of insertion loss are shown in Figure 19, and compared with the expected values in Table 6.

| Item | Party Line | | Rural Line | |
|---|---|---|---|---|
| | Calc. | Meas. | Calc. | Meas. |
| Effective Loss db | | | | |
| - Non loaded | 15.1 | 16.2 | 15.1 | 15.5 |
| - Loaded | 9.8 | 8.1 | 9.8 | 10.3 |
| Loading gain db | 5.3 | 8.1 | 5.3 | 5.2 |

TABLE 6

COMPARISON OF CALCULATED AND MEASURED LOSSES

EXPERIMENT II

Although these figures are not in as close agreement as are those of Experiment I, they do illustrate that the expected loading gain is realized.

The insertion loss curves of Figure 19 show a larger than expected increase in loss at high frequencies for both the non-loaded and loaded facility. This is most likely caused by the bridging capacitance of the subscriber terminating drops.

As anticipated loading improved the echo return loss performance of the loops. The non-loaded facilities both showed an echo return loss of 6.0 db. With loading applied this increased to 12.7 db for the party line and to 11.9 db for the rural line. The shape of the return loss curves is shown in Figures 20 and 21.

The loaded lines did, however, exhibit a decrease in singing margin from 5.7 to 3.8 db for the party line and from 5.9 to 3.0 db for the rural line. The minimum return loss occurred at the upper limit of the voice band and is due primarily to the position of the entrance cable load coil. The singing margin can be improved either by using a precise 0.5 end section, or by building out the line to a 0.8 section followed by a half-weight (44 mh.) coil.

Subscriber reaction to the improved performance on these lines was good. Both circuits have been in continuous service for some nine months. No operating difficulties have been encountered.

## 4. Experiment III — Kindersley

The subscriber loops used in this experiment were also operating circuits. Three rural party lines were loaded 88 mh/3.0 miles. Two of these three circuits were then equipped with an experimental series negative impedance repeater. The three modified circuits were left in service to verify stability and customer reaction.

### (a) Rural Circuit #50

Rural circuit #50 is a fairly standard loop composed of 5000 feet of 24 ga. non loaded cable and 17.0 miles of .109 steel wire. The expected effective loss of the main facility is 8.6 db, however the loss of subscriber taps raises this expected loss to 9.8 db at the subscriber's premise. The measured effective loss to the subscriber's premise was 10.2 db.

The circuit was loaded with one coil in the entrance cable, a matching transformer at the cable-open wire junction and five coils on the open wire. The effective improvement expected from loading is, therefore, 2.25 db. Thus the expected effective loss for the loaded facility 7.6 db. The measured value was 7.5 db.

The echo return loss for the non-loaded facility was 4.8 db. This value was increased to 10.3 db as a result of loading. Similarly the singing margin was increased from 4.0 to 4.8 db through loading.

Thus for this circuit the improvement in transmission performance as a result of loading was again achieved. The degree of improvement was predicted accurately by the formulae of Chapter III.

(b) Rural Circuits #48 and #49

These circuits are considerably longer than those previously encountered in the experimental work. Each circuit contains 5000 feet of 24 ga. non-loaded entrance cable and 10.0 miles of .104 Cd. Cu. (40% conductivity) open wire. In addition circuit 48 contains 26.0 miles, and circuit 49 contains 25.0 miles of .109 steel wire.

The calculated effective insertion loss, non-loaded, for circuit 48 is 13.7 db and for circuit 49 is 13.4 db. The measured losses were 14.2 and 14.0 db for the nearest and most remote subscriber on circuit 48, and 12.5 and 14.0 db for the corresponding subscribers on circuit 49.

Each circuit was loaded with one coil in the entrance cable, a matching transformer at the open wire-cable junction and ten coils on the open wire. Three of these ten coils were installed in the Cd. Cu. sections of the loops. The expected loading gain is, therefore 4.0 db and the expected effective losses are 9.7 and 9.4 db for circuits 48 and 49 respectively. Measured losses on circuit 48 were 9.0 and 9.8 db for the nearest and most remote subscriber. On circuit 49 the corresponding measured losses were 8.4 and 8.3 db respectively.

The addition of repeaters decreased the insertion loss still further. Figure 22 illustrates, for example, the insertion loss characteristics for the various configurations tested on circuit #49. As can be seen it was possible to reduce the effective loss of the facility to approximately 2.0 db by combining the improvements of loading and of repeatered operation.

The echo return loss for the two circuits again increased as a result of loading. The echo return loss of circuit 48 increased from 5.5 to 11.5 db, and of circuit 49 from 6.7 to 11.9 db when loaded. Singing margins did, however decrease from 5.2 to 2.8 db for circuit 48 and from 3.8 to 3.6 db for circuit 49. The lowest value of return loss was reached at 3200 cps on all three loaded circuits.

This singing margin was increased by the addition of repeaters. As shown in the circuit diagram, Figure 23, the repeater included a building out section which was adjusted for optimum return loss. Effectively this section extends the cable end section to 0.8, then terminates the built-out cable in a 44 mh. coil. By this means the optimum value of return loss can be realized.

A comparison of echo return loss and singing margin for circuit 49 with and without the repeater is shown in Table 7.

| Facility Condition | Echo Return Loss DB | Singing Point | |
|---|---|---|---|
| | | Margin - DB | Freq. CPS |
| Non Loaded | 5.5 | 3.8 | 3200 |
| Loaded | | | |
| No Repeater | 11.9 | 3.6 | 3200 |
| Nom. Gain ODB | 11.3 | 7.3 | 3000 |
| 1DB | 10.9 | 7.5 | 3200 |
| 2DB | 8.3 | 5.1 | 1750 |
| 3DB | 6.1 | 2.3 | 1750 |
| 3.5DB | 3.5 | 1.5 | 1750 |

TABLE 7

ECHO RETURN LOSS AND SINGING MARGINS

CIRCUIT #49 — EXPERIMENT III

It is apparent from this Table that a nominal gain of 2 db is suitable for circuit 49. In fact, because of an error in calibration of the repeater, the true effective gain for this setting was 4.5 db. Thus the net decrease in insertion loss for this particular circuit resulting from both loading gain and repeater gain was 8.5 db.

## 5. Conclusion

These experiments demonstrate that the anticipated improvement in performance as a result of loading .109 steel wire subscriber loops can be realized in practice. The loading gains were consistent with the results anticipated by the analysis of Chapter III. In addition the stability of the loading circuits has been demonstrated in normal service over periods of nine months.

Singing margin was the only operating parameter which showed a degradation as a result of loading. Experience with office mounted repeaters (Experiment III) showed that this degradation can be eliminated by using a 0.8 end section, and terminating the facility in a 44 mh. coil at the office.

When repeaters are applied to a loaded facility some adjustment of facility return loss is required to obtain optimum performance of the repeatered loop. This adjustment is normally obtained through an adjustable build-out of the end section. If the cable itself is terminated in a 0.8 end section, no further adjustment is possible. It is advisable, therefore, to terminate the facilities in a 0.5 end section, and to build out artificially to a longer section if improved singing margin is required.

Thus the effectiveness of loading .109 steel wire, and the accuracy of the analysis of Chapter III has been demonstrated. These results will now be used to define revised transmission limits for long rural subscriber loops.

# CHAPTER V

## LOOP DESIGN INFORMATION FOR .109 STEEL WIRE LOADED LOOPS

### 1. Introduction

The effectiveness of applying inductive loading to .109 steel wire lines has been demonstrated in Chapter III and Chapter IV. Limitations affecting the loading patterns, and effective loading gain formulae were also developed in those chapters. These limitations and gain factors are consolidated in this Chapter as a convenience for practical design of loaded steel wire loops.

Loading should be applied to .109 steel wire lines for local battery operation only. Existing design rules indicate that the transmission performance of .109 steel wire is adequate within the range of common battery operation. It is not necessary, therefore, to apply loading or repeaters to common battery loops.

### 2. Loading Pattern

The basic loading pattern for .109 steel wire is 88 millihenries spaced at three mile intervals. Minor deviations from this interval are not important since the cut-off frequency of the pattern is well above the highest frequency of interest for voice frequency telephone circuits. Generally, however, each loading interval should be within 10% of its nominal value to avoid impedance irregularities.

This loading pattern should be continuous through incidental lengths of other open wire facility types. No impedance matching is necessary at junctions of different open wire types.

Incidental lengths of cable should be loaded with an H88 pattern. An adequate impedance match may be obtained by installing an autotransformer of impedance ratio 2.0:1 at the open wire cable junction.

Impedance irregularities at open wire-cable junctions may be avoided by installing a transformer of impedance ratio 2.0:1 at the junction, and by using complementary end sections on the two facility types. If, for example, the last load coil on a cable is 2100 feet (0.35 section) from the junction, then the first load section on the open wire should be a (1 - 0.35) =.65 section. That is, in this example, the first load coil on the open wire should be 3.0 X .65 = 1.95 miles from the junction.

Terminating end sections at central offices are normally 0.5 sections. Improved high frequency return loss can be obtained if terminating end sections are extended to 0.8 section and built-out with a 44 millihenry coil. Adjustment of the end section impedance is necessary, however, to obtain optimum return loss for repeatered operation. Thus if the use of repeaters is contemplated it is adviseable to terminate loaded loops in a 0.5 section, and to build-out artificially if improved high frequency return loss is required.

The cut-off frequency of the loading pattern is determined by the inductance and capacitance in each loading section. Bridged taps or subscriber drops resemble an added capacitance at their junction with the main subscriber loop. The cut-off frequency will, therefore, be decreased if the pattern is extended past a bridged tap. For this reason no load coils should be placed on a circuit beyond the first subscriber drop.

## 3. Loading Gain Factors

The effective loading gain is defined by equation (21) as:

$$\text{Loading Gain} = (\Sigma A_iN_i) - 1.5 \text{ db} \qquad (21)$$

in which $A_i$ = the loading gain per coil for facility type i, and

$N_i$ = the number of loading coils in facility type i.

The appropriate values of A are:

| | | |
|---|---|---|
| Cable: (H88 patterns) | 19 ga. | 1.1 |
| | 22, 24, 26 ga. | 1.5 |
| Open Wire: (88 mh./3.0 mi.) | .109 steel | 0.45 |
| | .104 Cd. Cu. (40%) | 0.27 |
| | .104 Cu. | 0.09 |

## 4. Mismatch Losses

Mismatch losses occur as a result of the interconnection of dissimilar facilities within a subscriber loop. The value of these losses is calculated on the assumption that each facility type is sufficiently long that it displays its characteristic impedance.

Since this condition seldom exists on a subscriber loop the calculated mismatch loss can be only an estimate of the effect of the impedance discontinuity.

The Rural Electrical Administration[10] has suggested that mismatch loss factors be applied only if the loss of the incidental facility type is greater than 2 db. With this assumption the applicable mismatch loss factors for .109 steel wire loaded 88 mh/3.0 miles are:

| Facilities Joined | Mismatch Loss |
|---|---|
| .104 Copper to .104 Cd. Cu. (40%) | 0.0 db |
| .104 Copper to .109 Steel | 0.4 db |
| .104 Cd. Cu. to .109 Steel | 0.4 db |
| H88 loaded cable to loaded Open Wire | 0.2 db |

Provided that:

(a) Open wire facilities are loaded 88 mh/3.0 miles.

(b) A matching transformer of impedance ratio 2.0:1 is inserted at the open wire-cable junction.

---

[10] Rural Electrical Administration Telephone Engineering and Construction Manual, Section 422, Paragraph 5.02, Issue 4, dated August, 1959.

## 5. Limiting Loop Lengths

The net transmission improvement which can be achieved through loading depends upon the length and types of facilities used in the loop, and the location of the subscriber closest to the central office. These vary so widely in practice that it is not possible to define a limiting loop with any practical significance.

A concept of the value of loading may be gained, however, by a comparison of facility lengths which yield comparable transmission performance. The following examples provide such a comparison for representative subscriber loops.

### Example I

Table 8 shows the maximum ranges for a .109 steel wire facility whose transmission performance is equal to that of a limiting loop, i.e. $\frac{T + R}{2} = 0.0$ db. It has been assumed that all subscriber drops are within the last ten miles of the loop, and that the loading pattern terminates on the office side of the first subscriber drop. The use of modern type (1953 or later) telephone sets has also been assumed.

| | REPEATER GAIN - DB | | | | |
|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 |
| Max. Range (Miles): | | | | | |
| Non Loaded | 34.9 | 37.7 | 40.4 | 43.2 | 45.9 |
| Loaded | 44.4 | 49.6 | 52.6 | 58.9 | 63.0 |
| Increased Range (Miles) | 9.5 | 11.9 | 12.2 | 15.7 | 17.1 |
| No. of Load Coils | 11 | 13 | 14 | 16 | 17 |

TABLE 8

PERMISSIVE RANGES FOR LIMITING LOOPS OF .109 STEEL WIRE

Example II

Table 9 is a similar comparison of ranges for a subscriber loop containing 5000 feet of 24 ga. entrance cable extended by .109 steel wire. The same assumptions have been made concerning the location and type of telephone sets on the loop. The ranges shown are the maximum lengths of the steel wire extension.

| | REPEATER GAIN - DB | | | | |
|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 |
| Max. Range (Miles): | | | | | |
| Non Loaded | 28.8 | 31.6 | 34.4 | 37.1 | 39.9 |
| Loaded | 41.2 | 46.5 | 50.2 | 55.7 | 61.0 |
| Increased Range Miles | 12.4 | 14.9 | 15.8 | 18.6 | 21.1 |
| No. of Load Coils | 11 | 13 | 14 | 16 | 18 |

TABLE 9

PERMISSIVE RANGES FOR LIMITING LOOPS CONTAINING
5000 FT. 24 GA. CABLE EXTENDED BY .109 STEEL WIRE

It is apparent from these examples that operating ranges for .109 steel wire loops of the order of 40 - 45 miles can be achieved by loading. By installing office mounted repeaters on the loaded facility the permissive transmission range can be extended to about 60 miles.

## 6. Conclusion

The object of this investigation was to examine methods by which the permissive transmission range of steel wire rural subscriber circuits could be extended economically to about 50 miles. The study has shown that this extension is possible if the steel wire circuits are loaded to a pattern of 88 mh/3.0 miles, and if office mounted repeaters are installed on those circuits longer than about 40 - 45 miles.

In addition to decreasing the insertion loss of the subscriber circuit, the application of loading improves its frequency response and return loss. These improvements are achieved with negligible degradation of sidetone performance, and with negligible increase in wet to dry weather transmission differential provided the recommended loading pattern is used.

Design factors for this loading pattern have been prepared, and have been verified in the field. With these factors rural subscriber loops may be designed using the procedures which have been adopted in North America.

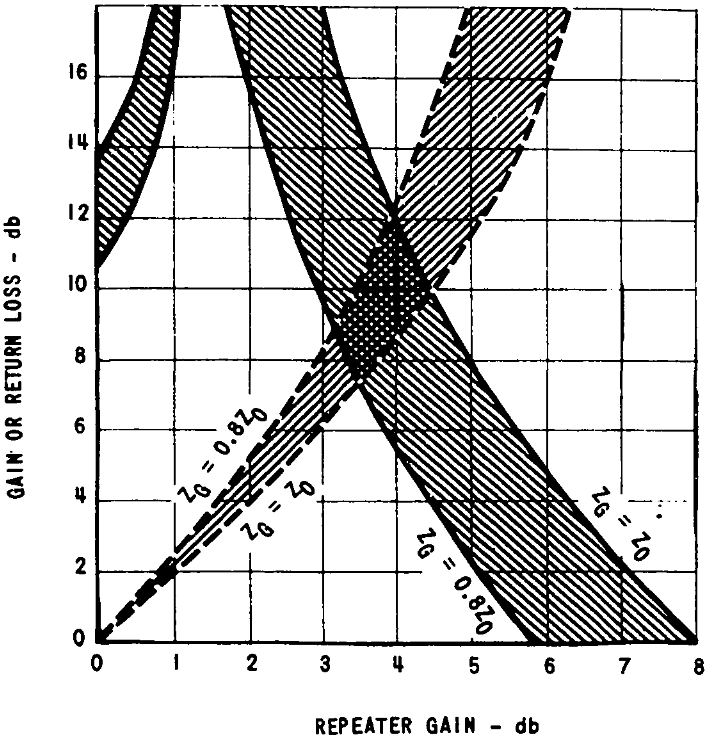


FIGURE 3
OPERATING LIMITATIONS OF
CIRCUIT OF FIG. 2
$Z_0 = 1425 \angle 26.1^\circ\Omega$
$Z_{0FF} = 905 \angle 4.8^\circ\Omega$
$0.8Z_0 \leq Z_G \leq Z_0$
RETURN LOSS ▨
GAIN 2 TANDEM CCTS ▨

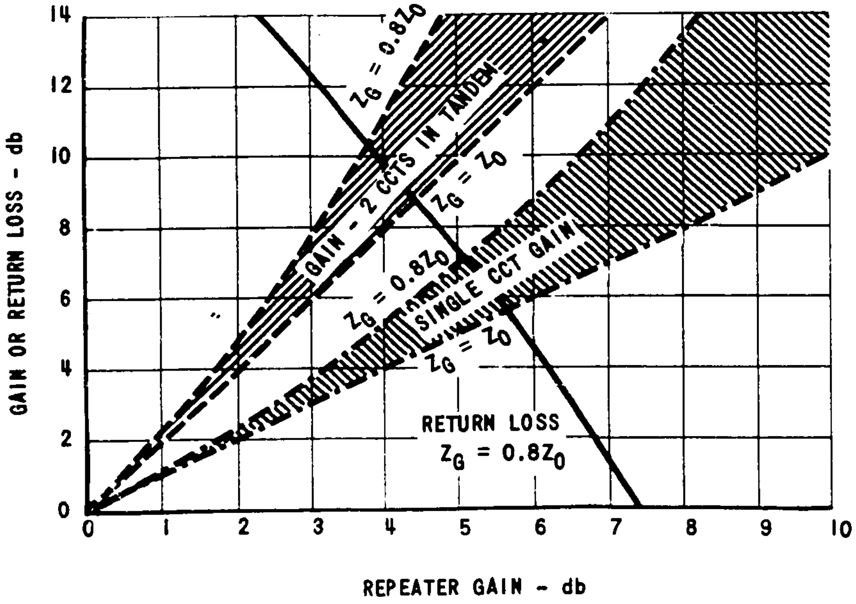


FIGURE 5
OPERATING LIMITATIONS OF
CIRCUIT OF FIG. 4
$Z_0 = 1425 \angle 26.1^\circ\Omega$
$Z_{0FF} = 905 \angle 4.8^\circ\Omega$
$0.8Z_0 \leq Z_G \leq Z_0$
RETURN LOSS ▨
GAIN 2 TANDEM CCTS ▨

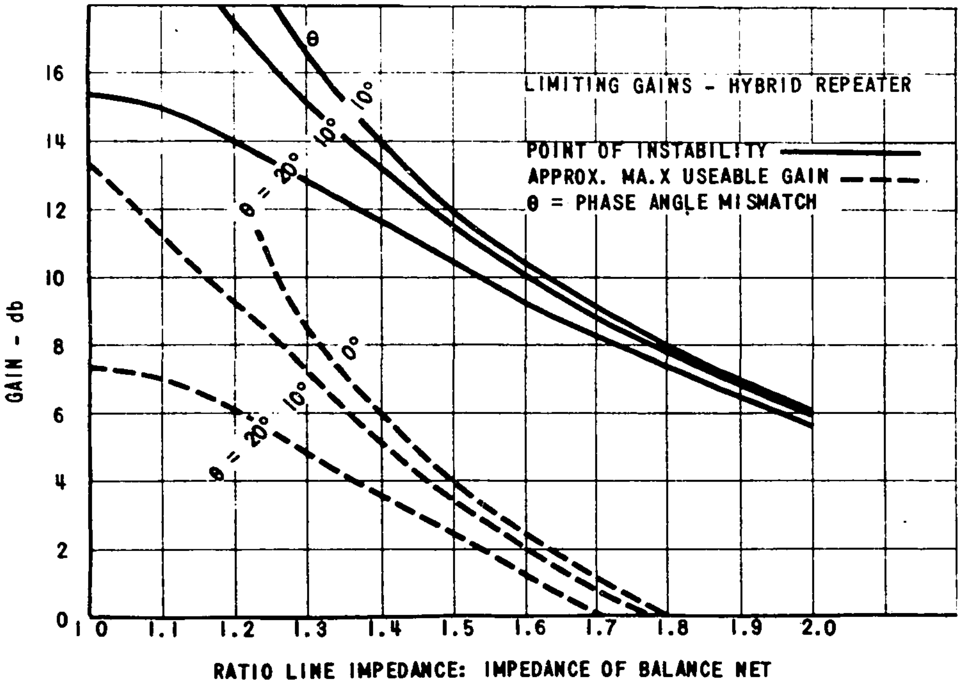


FIGURE 9

FIGURE 10
VARIATION OF $\alpha$ AND $Z_0$ VS. L
.109 STEEL WIRE
1000 CPS
L - INDUCTANCE
$\alpha$ - ATTENUATION CONSTANT
$Z_0$ - CHARACTERISTIC IMPEDANCE

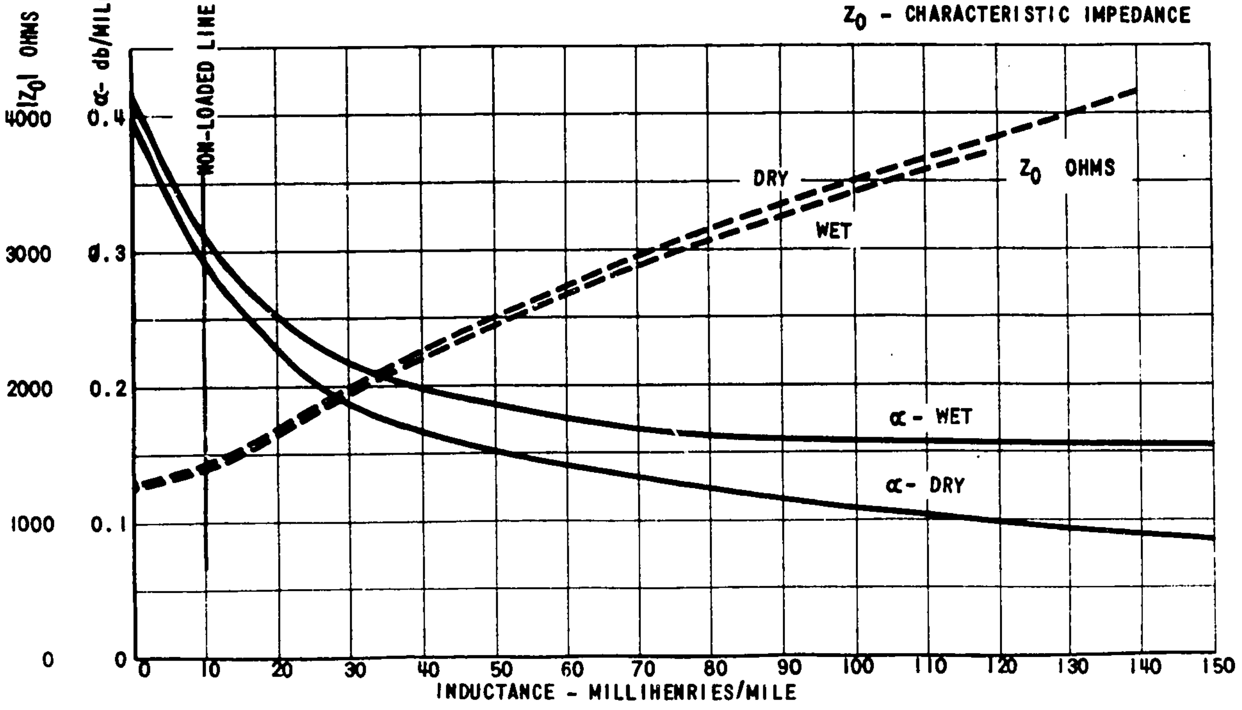


FIGURE 11
SIDETONE SUPPRESSION
554 TYPE TELEPHONE

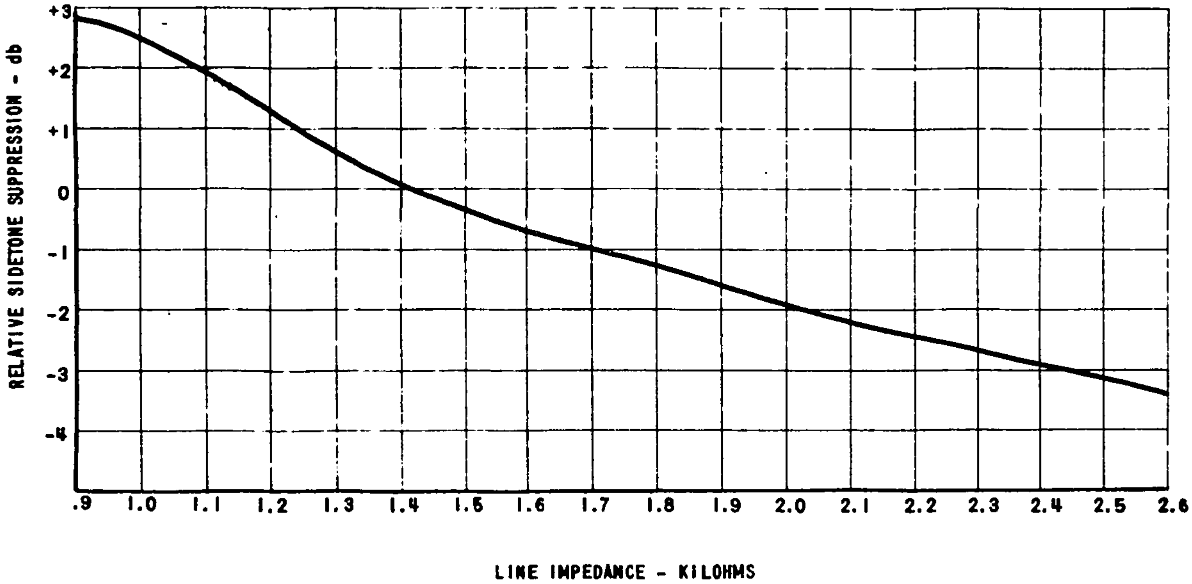
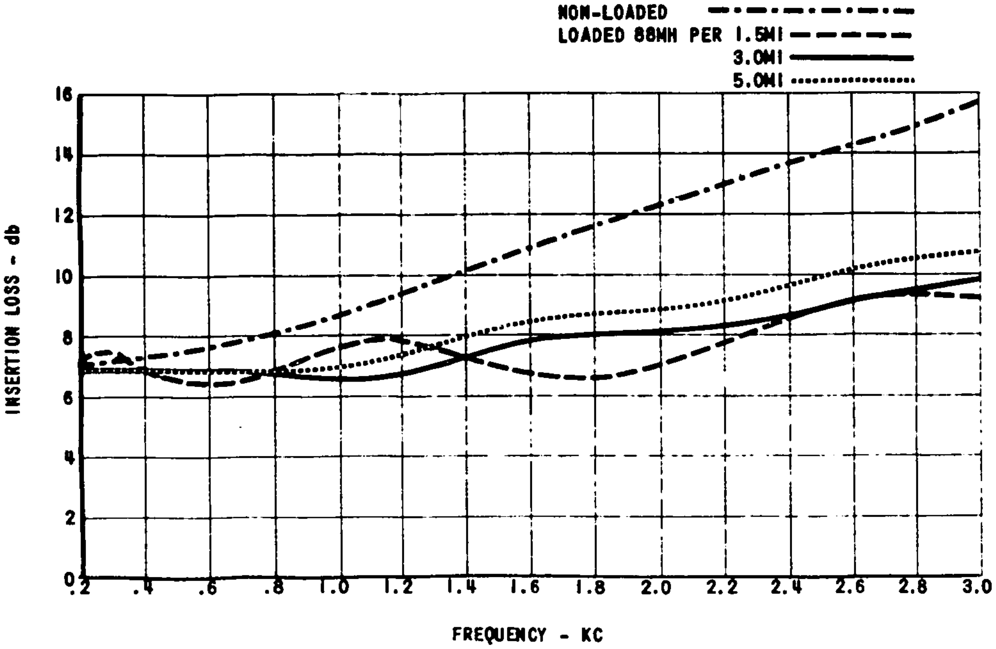


FIGURE 12
INSERTION LOSS OF
30 MI. .109 STEEL WIRE



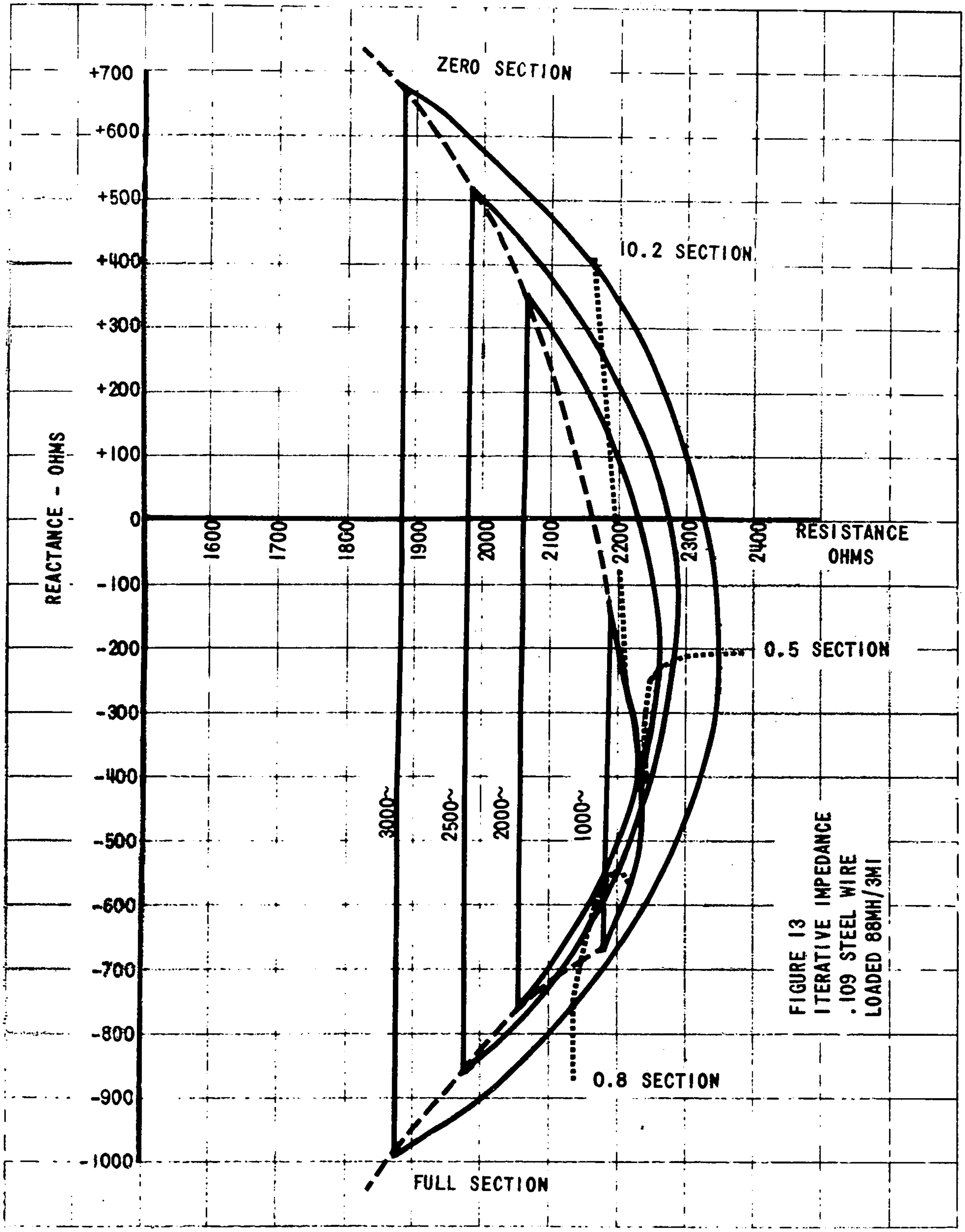


FIGURE 13
ITERATIVE IMPEDANCE
.109 STEEL WIRE
LOADED 88MH/3MI

FIGURE 14
CALCULATED INSERTION LOSS
30MI .109 STEEL WIRE - DRY
——— NON-LOADED
– – – LOADED 88MH/3.0MI
INCL. MATCHING TRANSFORMER AT OFFICE
CIRCUIT TERMINATED IN TYPE 554 TELEPHONE

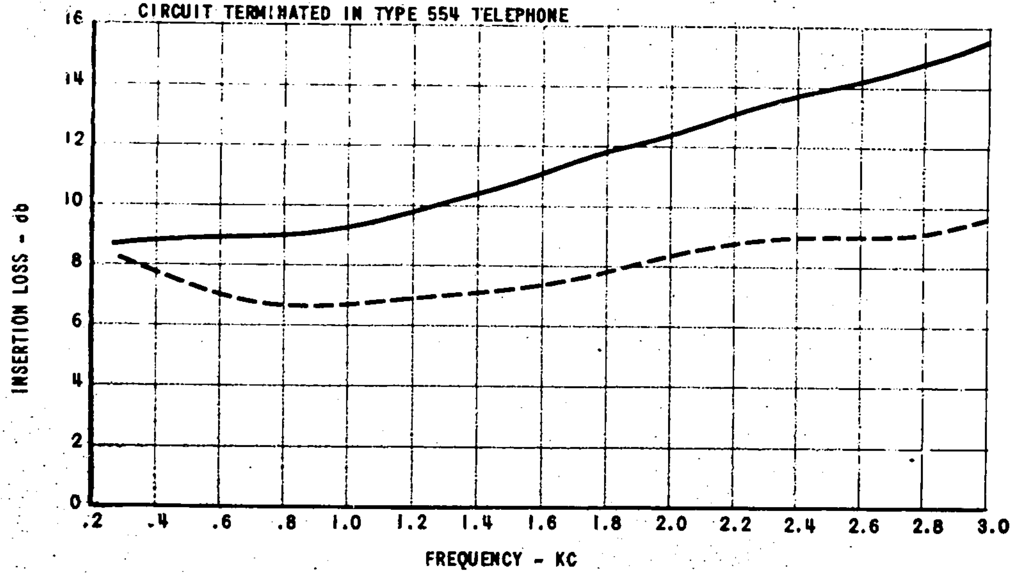


FIGURE 15
CALCULATED INSERTION LOSSES
.109 STEEL WIRE - DRY

| | 1000~ | 1500~ |
|---|---|---|
| NON-LOADED | ——— | ········· |
| LOADED 88MH/3MI | —·—· | – – – |

TERMINATION 554 TELEPHONE SET

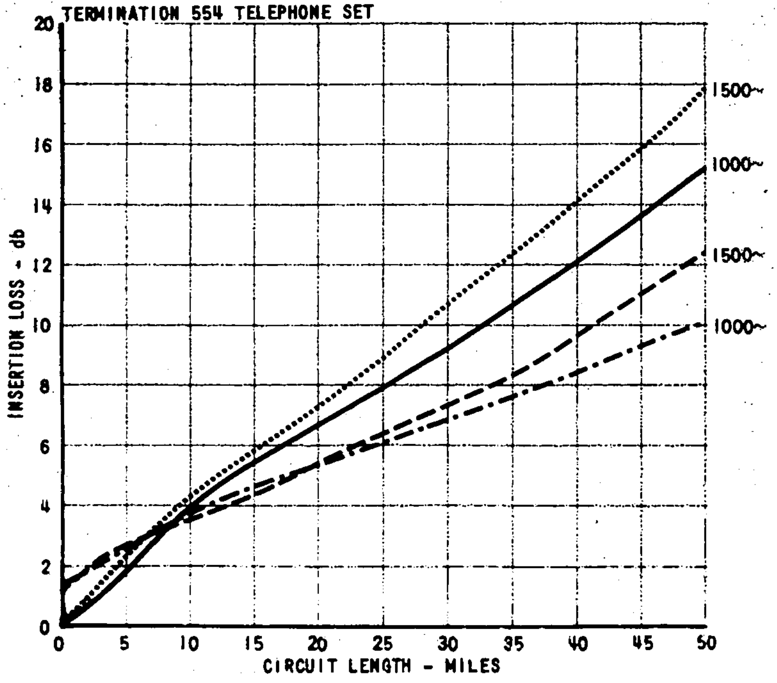


FIGURE 16
RETURN LOSS TO 900Ω + 2μf
30MI 109 STEEL WIRE
TERMINATED IN 554 TELEPHONE SET

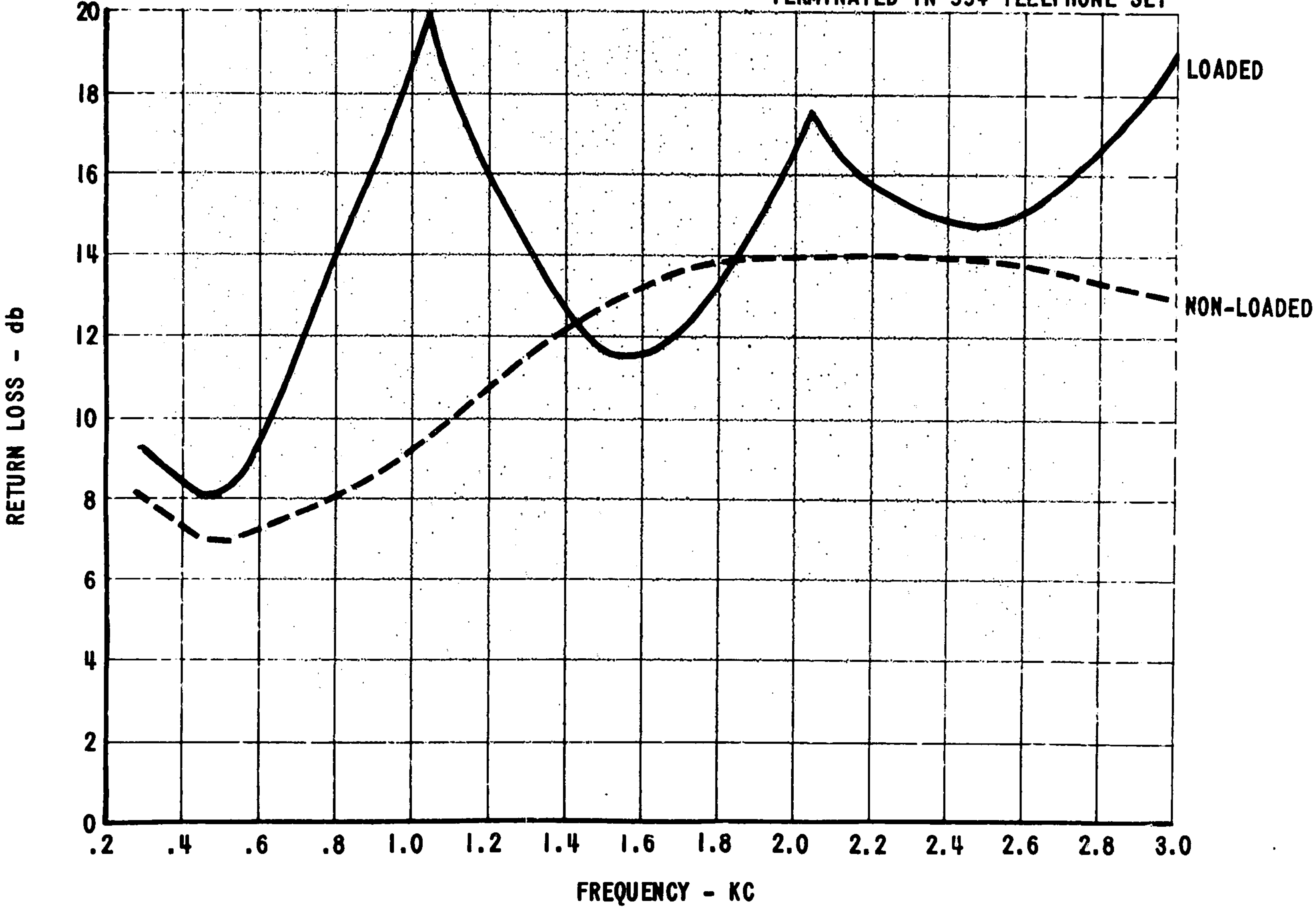


FIGURE 16
RETURN LOSS TO 900Ω + 2μf
30MI 109 STEEL WIRE
TERMINATED IN 554 TELEPHONE SET

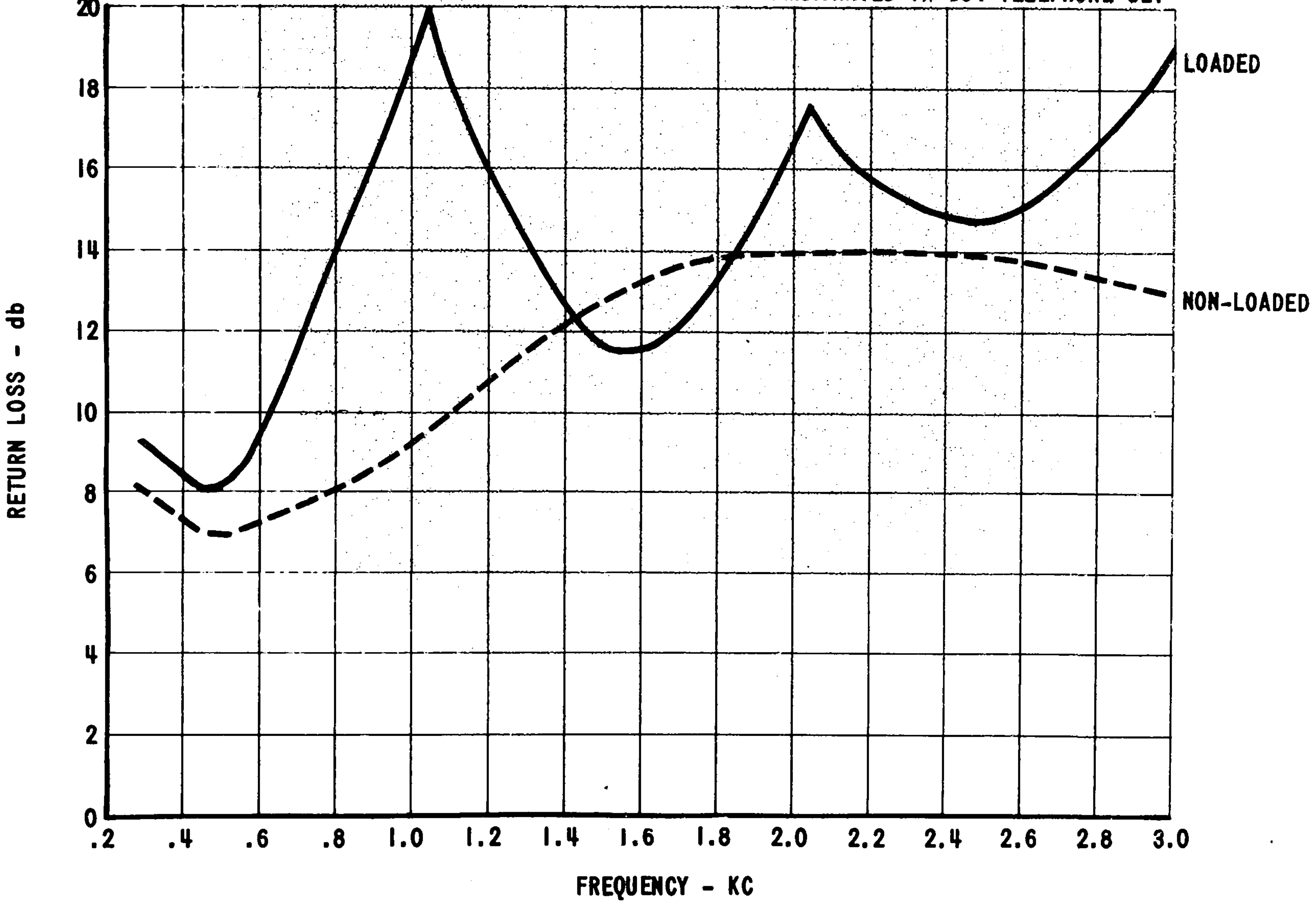
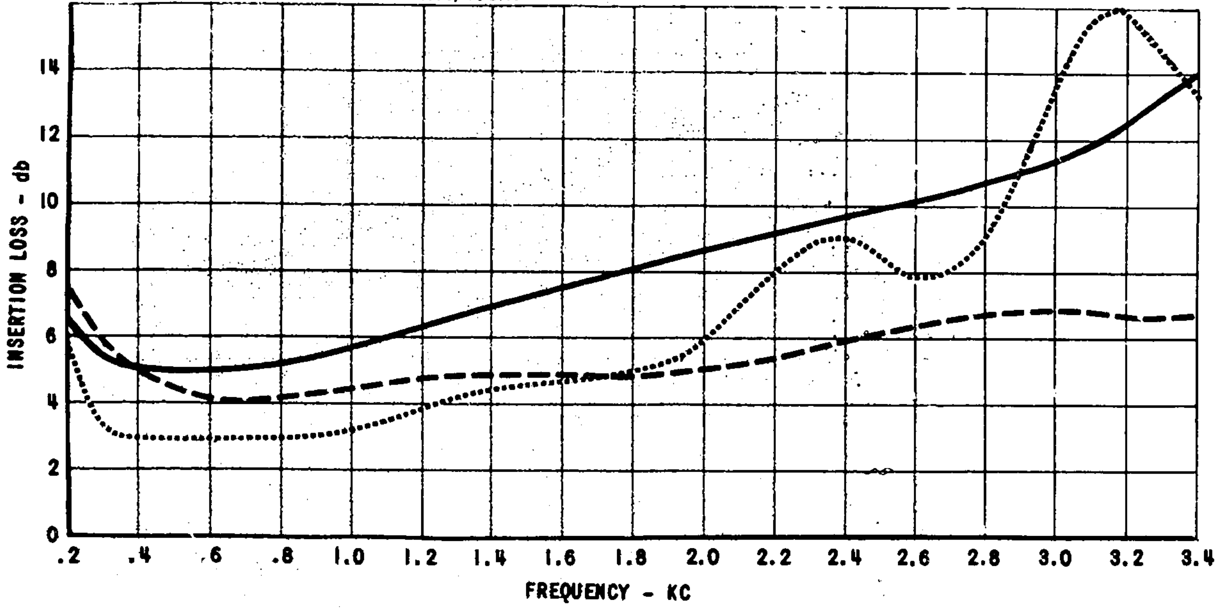


FIGURE 17
FACILITY INSERTION LOSS
EXPERIMENT I BANCROFT-MAYNOOTH, ONT.
LOADING PATTERN NON-LOADED ———
LOADED 88MH/3.0MI — —
LOADED 176MH/1.5MI ······



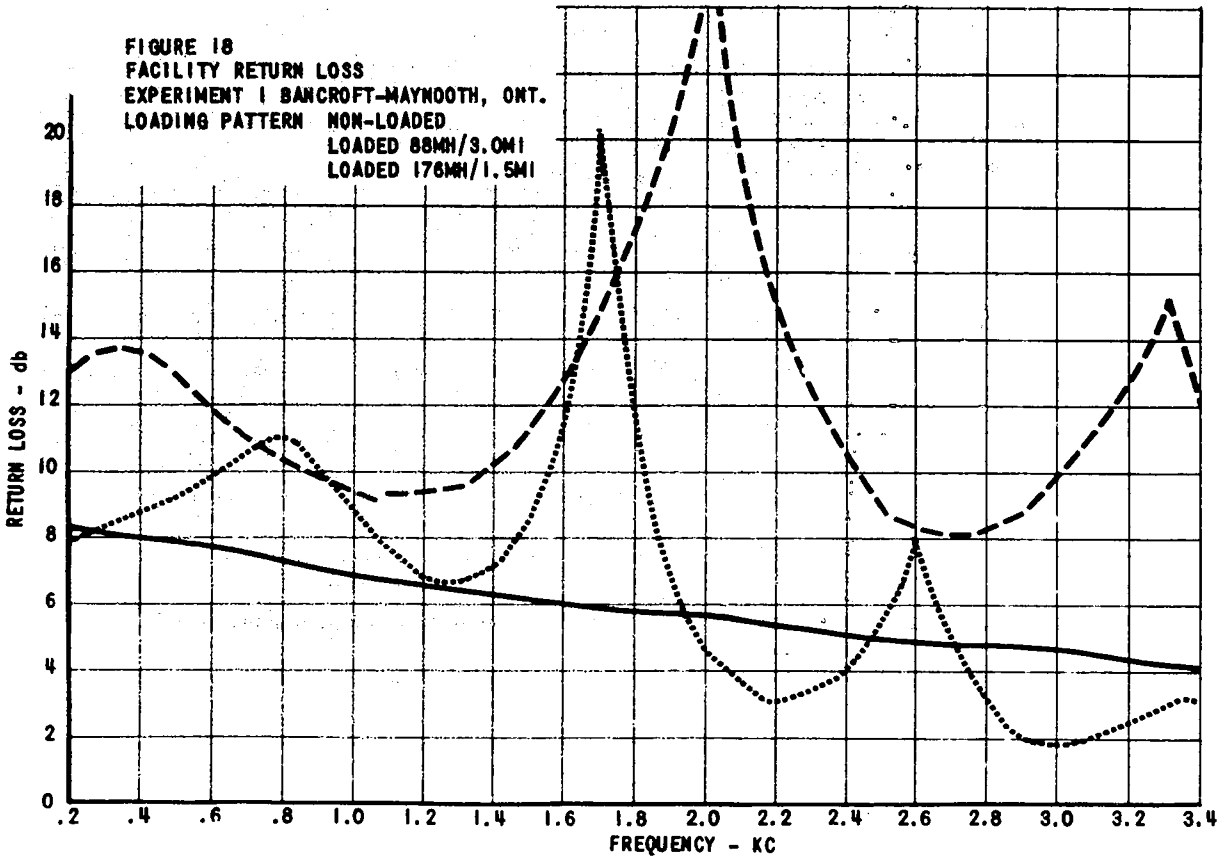
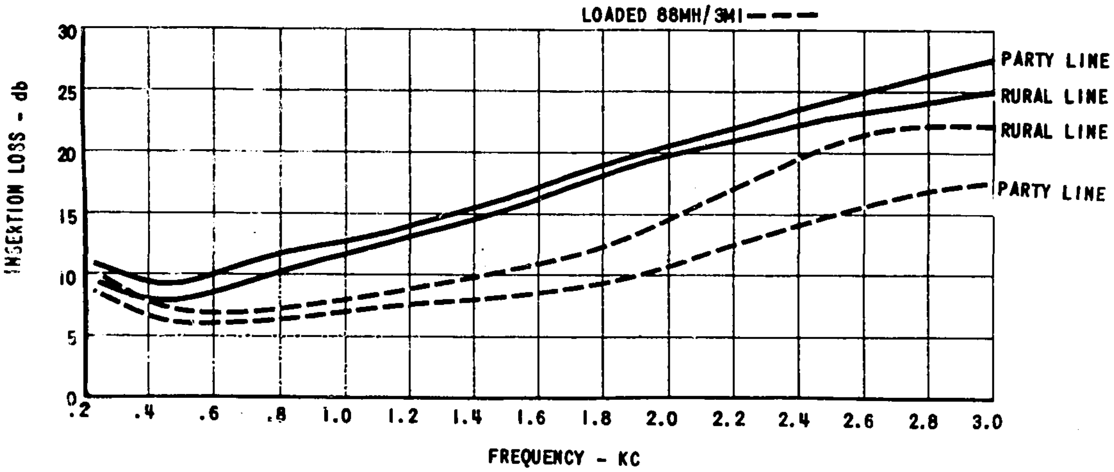


FIGURE 18
FACILITY RETURN LOSS
EXPERIMENT I BANCROFT-MAYNOOTH, ONT.
LOADING PATTERN NON-LOADED
LOADED 88MH/3.0MI
LOADED 176MH/1.5MI

FIGURE 19
FACILITY INSERTION LOSS
EXPERIMENT 2 ESTEVAN, SASK.
LOADING PATTERN NON-LOADED ————
LOADED 88MH/3MI — — —



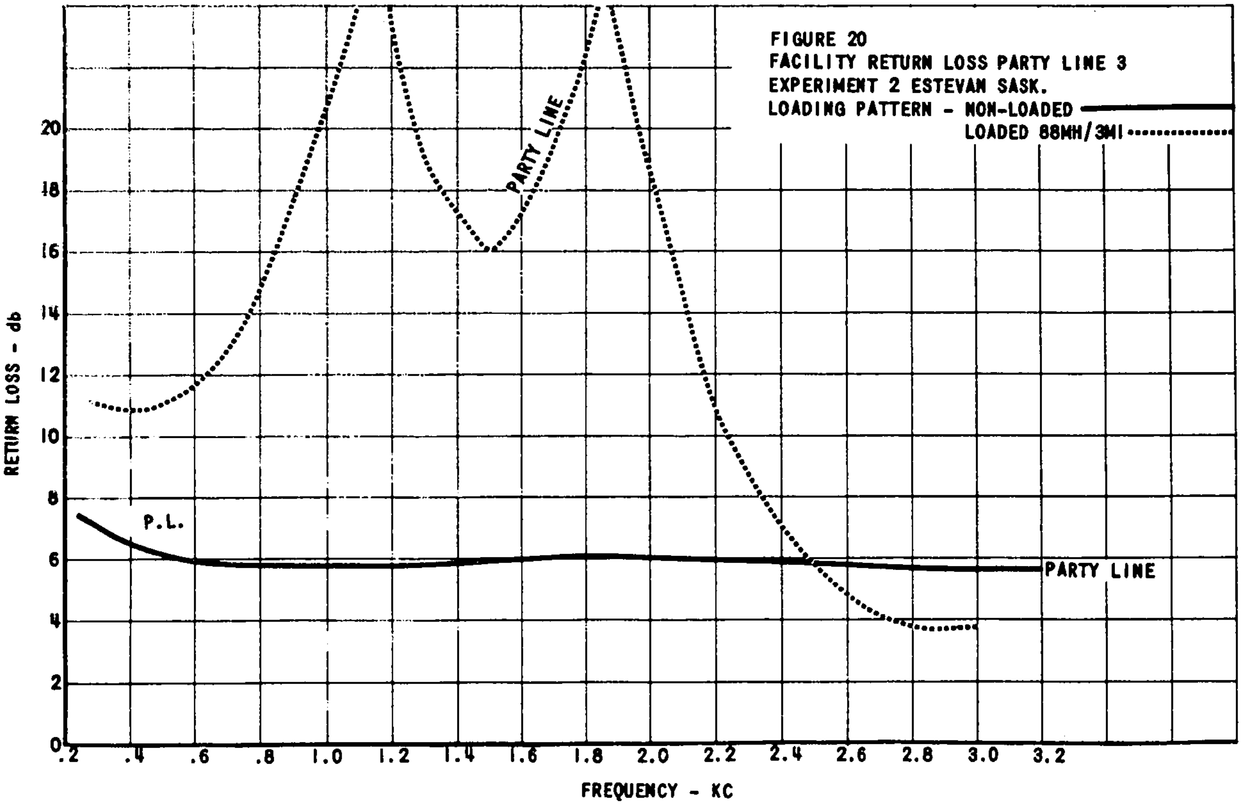


FIGURE 20
FACILITY RETURN LOSS PARTY LINE 3
EXPERIMENT 2 ESTEVAN SASK.
LOADING PATTERN - NON-LOADED ————
LOADED 88MH/3MI ··············

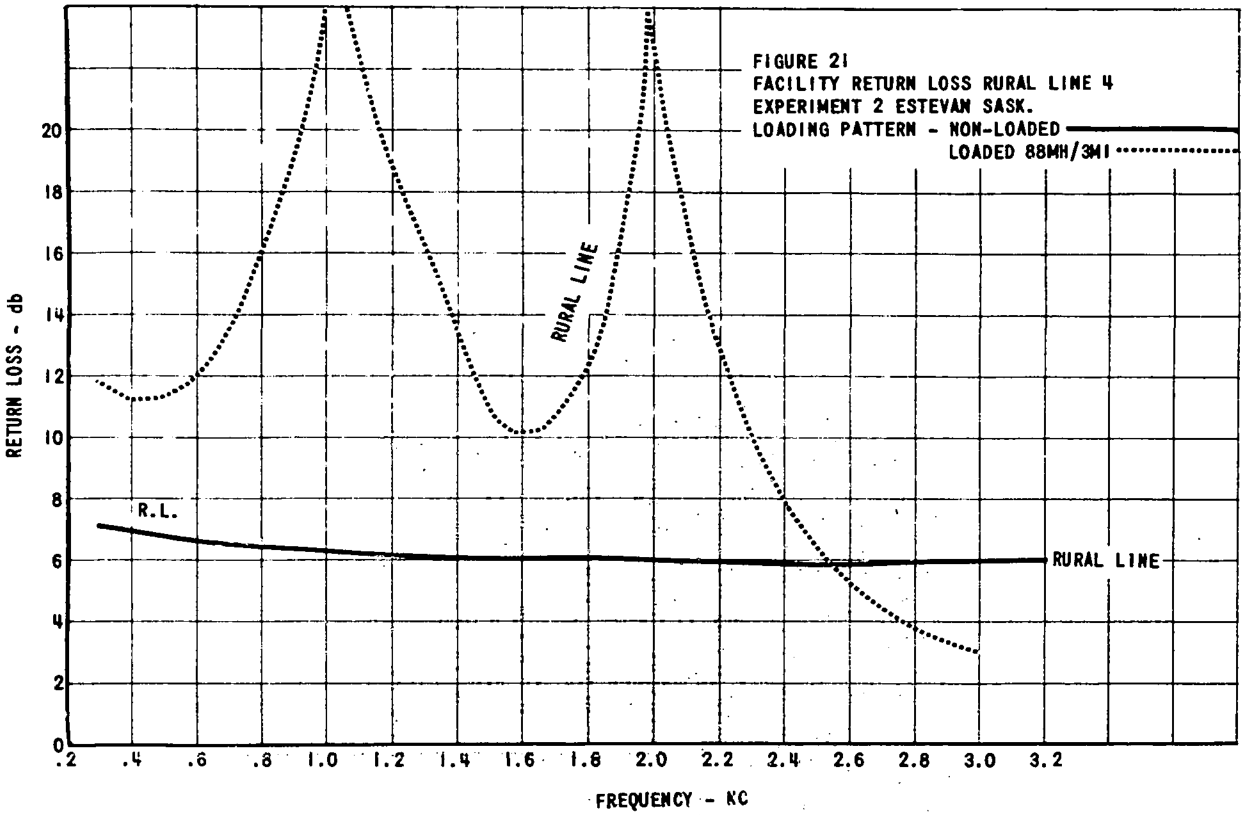


FIGURE 21
FACILITY RETURN LOSS RURAL LINE 4
EXPERIMENT 2 ESTEVAN SASK.
LOADING PATTERN - NON-LOADED
LOADED 88MH/3MI

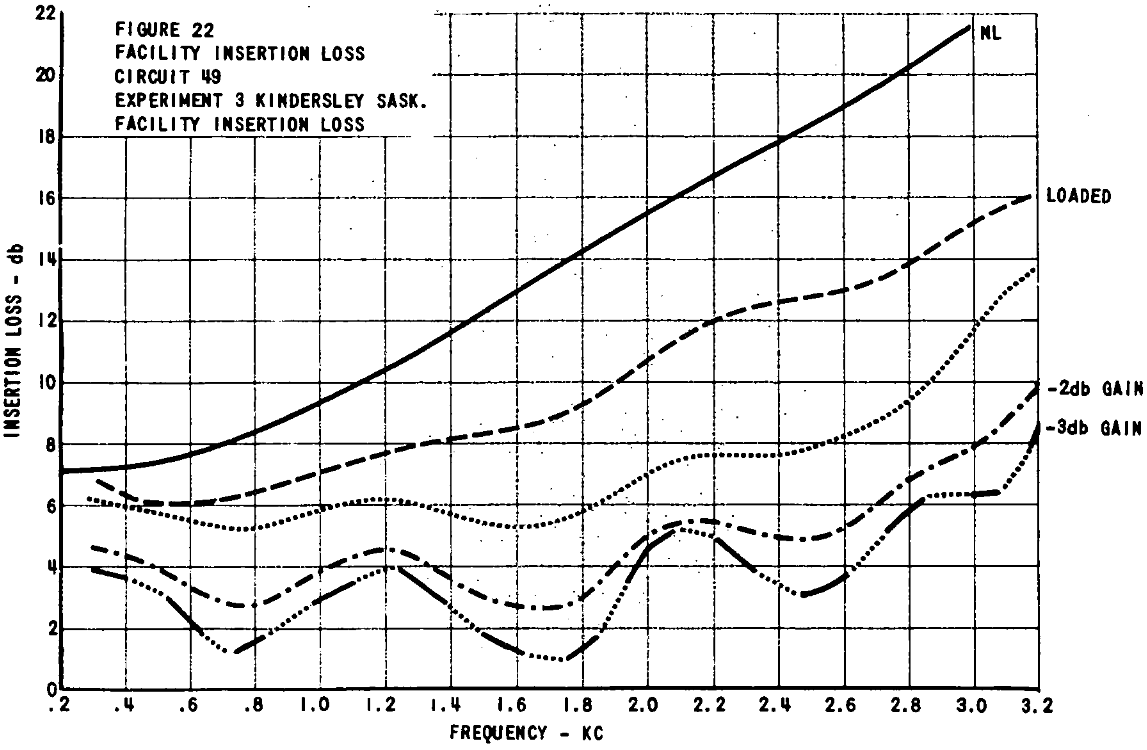


FIGURE 22
FACILITY INSERTION LOSS
CIRCUIT 49
EXPERIMENT 3 KINDERSLEY SASK.
FACILITY INSERTION LOSS

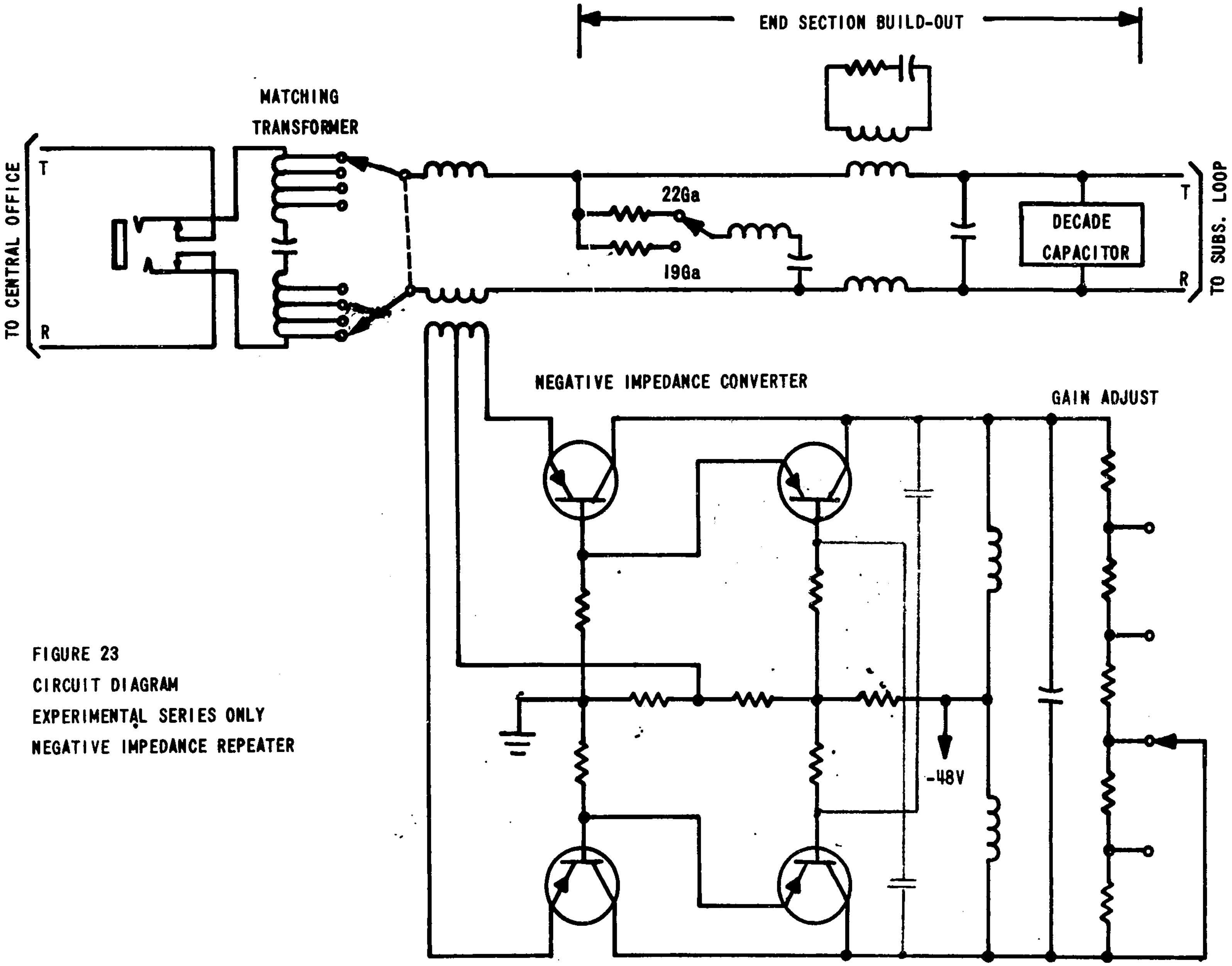
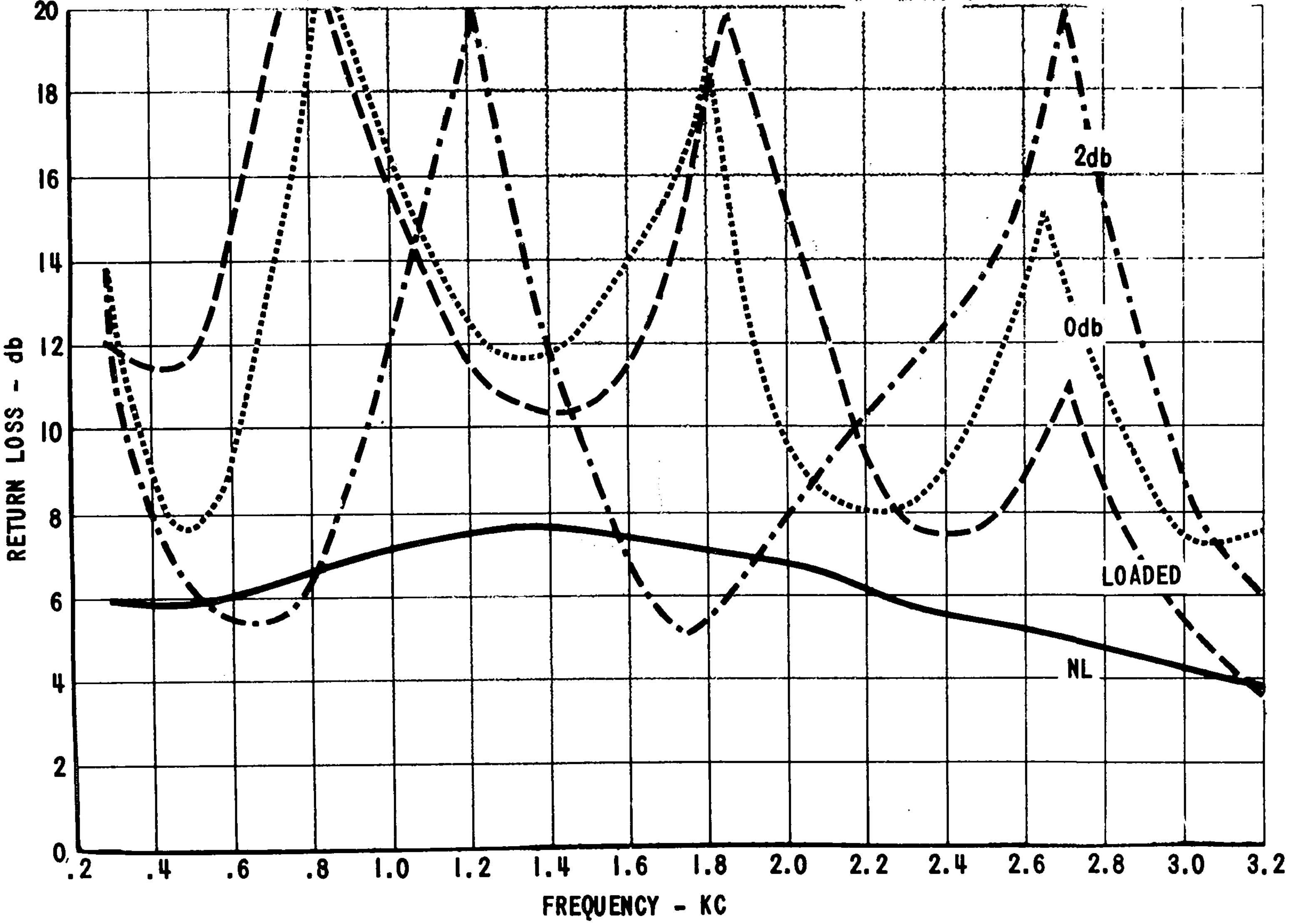


FIGURE 23
CIRCUIT DIAGRAM
EXPERIMENTAL SERIES ONLY
NEGATIVE IMPEDANCE REPEATER

FIGURE 24
FACILITY RETURN LOSS
CIRCUIT 49
EXPERIMENT 3 KINDERSLEY SASK.



# APPENDIX I

## CHARACTERISTICS OF TYPICAL SUBSCRIBER LOOP FACILITIES

### 1. General

The characteristics listed below have been used for prediction of the performance of the subscriber loop facilities as detailed in the body of this report. Except where otherwise noted the line characteristics listed below have been extracted from the AB sections of Bell System Practices. The impedance values for loading coils, and for the rural telephone sets have been obtained by measurement.

### 2. .109 Steel Wire Line, 12 inch Spacing

#### (a) Secondary Constants

| Freq. | Atten. - db/mile | | Phase Shift - rad/mi | | Characteristic Imped. Ohms | |
|---|---|---|---|---|---|---|
| Kc/s | Dry | Wet | Dry | Wet | Dry | Wet |
| .3 | .181 | .207 | .028 | .026 | 1754-j1314 | 1818-j1122 |
| 1.0 | .289 | .313 | .067 | .068 | 1279-j629 | 1274-j578 |
| 2.0 | .407 | .436 | .121 | .095 | 1142-j443 | 1130-j413 |
| 3.0 | .528 | .560 | .167 | .169 | 1054-j383 | 1042-j360 |
| 4.0 | .623 | .660 | .212 | .215 | 1004-j339 | 991-j320 |

## (b) Primary Constants - Calculated from (a)

| | DRY | | | | WET | | | |
|---|---|---|---|---|---|---|---|---|
| Freq. | R | L | G | C | R | L | G | C |
| Kc/s | Ohms | MH | mhos | fd | Ohms | MH | mhos | fd |
| .3 | 73.2 | 11.55 | -.0642(?) | .0084 | 72.4 | 10.91 | 3.09 | .0085 |
| 1.0 | 84.7 | 10.31 | .2203 | .0083 | 85.1 | 10.48 | 3.35 | .0087 |
| 2.0 | 107.0 | 9.35 | -.1049(?) | .0084 | 95.9 | 6.89(?) | 12.08(?) | .0070(?) |
| 3.0 | 128.0 | 8.103 | .0971 | .0084 | 128.0 | 8.11 | 5.24 | .0087 |
| 4.0 | 143.8 | 7.502 | .1057 | .0084 | 144.1 | 7.51 | 6.01 | .0087 |

## 3. Entrance Cables

### (a) 22 Gauge

| Freq. | R | L | G | C | $\alpha$ | B | Ch. Impedance |
|---|---|---|---|---|---|---|---|
| Cps | Ohms | MH | mhos | fd | Nep/mi | Rad/mi | Ohms |
| 50 | 171.0 | .798 | .05 | .082 | .04695 | .04692 | 1825-j1819 |
| 100 | 171.0 | .798 | .12 | .082 | .06635 | .06639 | 1292-j1285 |
| 200 | 171.0 | .798 | .21 | .082 | .09368 | .09404 | 915-j907 |
| 300 | 171.0 | .798 | .29 | .082 | .1146 | .1154 | 748-j740 |
| 500 | 171.0 | .798 | .46 | .082 | .1475 | .1494 | 581-j571 |
| 1000 | 171.1 | .798 | 1.2 | .082 | .2071 | .2128 | 414-j401 |
| 2000 | 171.3 | .798 | 3.2 | .082 | .2889 | .3053 | 297-j279 |
| 3000 | 171.5 | .798 | 5.7 | .082 | .3491 | .3796 | 246-j225 |

(b) <u>24 Gauge</u>

| Freq. | R | L | G | C | α | B | Ch. Impedance |
|---|---|---|---|---|---|---|---|
| Cps | Ohms | MH | mhos | fd | Nep/mi | Rad/mi | Ohms |
| 50 | 274.0 | .912 | .05 | .072 | .05571 | .05563 | 2465-j2457 |
| 100 | 274.0 | .912 | .10 | .072 | .07873 | .07873 | 1744-j1737 |
| 200 | 274.0 | .912 | .19 | .072 | .1112 | .1115 | 1234-j1227 |
| 300 | 274.0 | .912 | .26 | .072 | .1361 | .1366 | 1009-j1001 |
| 500 | 274.0 | .912 | .41 | .072 | .1753 | .1768 | 783-j773 |
| 1000 | 274.0 | .912 | 1.0 | .072 | .2466 | .2513 | 557-j544 |
| 2000 | 274.1 | .912 | 2.8 | .072 | .3455 | .3590 | 398-j381 |
| 3000 | 274.2 | .912 | 5.1 | .072 | .4189 | .4443 | 329-j307 |

(c) <u>26 Gauge</u>

| Freq. | R | L | G | C | α | B | Ch. Impedance |
|---|---|---|---|---|---|---|---|
| Cps | Ohms | MH | mhos | fd | Nep/mi | Rad/mi | Ohms |
| 50 | 440.0 | .952 | .05 | .069 | .06911 | .06901 | 3190-j3181 |
| 100 | 440.0 | .952 | .10 | .069 | .0977 | .09763 | 2257-j2249 |
| 200 | 440.0 | .952 | .18 | .069 | .1381 | .1382 | 1597-j1589 |
| 300 | 440.0 | .952 | .24 | .069 | .1690 | .1693 | 1304-j1589 |
| 500 | 440.0 | .952 | .39 | .069 | .2179 | .2189 | 1012-j1003 |
| 1000 | 440.0 | .952 | 1.0 | .069 | .3071 | .3106 | 718-j707 |
| 2000 | 440.0 | .952 | 2.7 | .069 | .4315 | .4421 | 511-j496 |
| 3000 | 440.1 | .952 | 4.9 | .069 | .5251 | .5450 | 421-j402 |

## 4. 88 Millihenry Load Coil

| Freq. | L | R |
|---|---|---|
| Kc/s | MH | Ohms |
| 1.0 | 87.99 | 6.0 |
| 1.5 | 87.994 | 6.5 |
| 2.0 | 87.995 | 7.0 |
| 2.5 | 88.016 | 7.5 |
| 3.0 | 88.040 | 8.0 |

## 5. Telephone Sets

Impedance at line terminals measured with an input level of -10 dbm, and with 3.0 volt talking battery.

| Freq. | Impedance - Ohms | |
|---|---|---|
| CPS | Modern Type (1962) | Older Type (About 1945) |
| 200 | 175-j760 | 73-j595 |
| 400 | 333-j221 | 75-j130 |
| 600 | 365-j51 | 102+j92.3 |
| 800 | 415+j51 | 131+j226 |
| 1000 | 483+j85 | 181+j355 |
| 1200 | 495+j119 | 219+j411 |
| 1400 | 517+j143 | 227+j510 |
| 1600 | 484+j143 | 258+j608 |
| 1800 | 472+j163 | 306+j688 |
| 2000 | 472+j177 | 354+j760 |
| 2200 | 492+j199 | 401+j824 |
| 2400 | 562+j233 | 434+j889 |
| 2600 | 560+j221 | 493+j928 |
| 2800 | 611+j259 | 539+j970 |
| 3000 | 613+j293 | 574+j993 |
| 3200 | 651+j298 | 581+j1050 |

# APPENDIX II

## DERIVATION OF LINE TRANSMISSION EQUATIONS

### 1. T Section Equivalent

The T section equivalent circuit of a line is as illustrated in Figure 25.

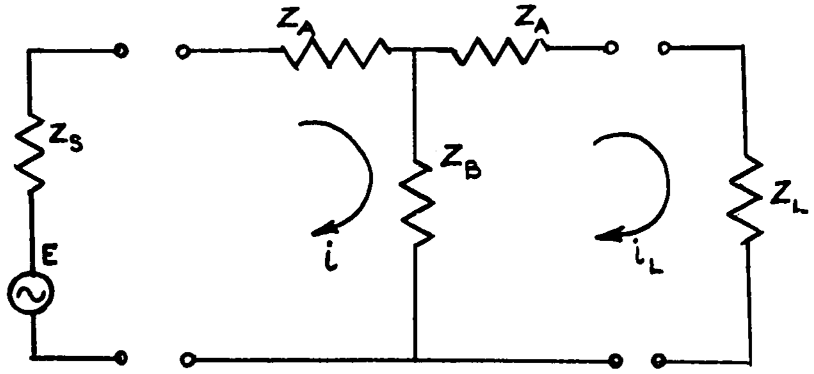


FIGURE 25

T SECTION EQUIVALENT CIRCUIT OF A HOMOGENEOUS TRANSMISSION LINE

The particular impedances are:

$Z_s$ = source impedance

$Z_L$ = load impedance

$Z_A$ = $Z_o \tanh \frac{\gamma L}{2}$

$Z_B$ = $Z_o / \sinh \gamma L$

$Z_o$ = line characteristic impedance

$\gamma$ = propagation constant

L = line section length

## 2. Terminal Impedances Connected Directly to Line

### (a) Input Impedance

The input impedance, $Z_{in}$ is given by:

$$Z_{in} = Z_A + \frac{Z_B \ (Z_A+Z_L)}{Z_A+Z_B+Z_L}$$

The substitution of the appropriate values for $Z_A$ and $Z_B$ yields, after simplification:

$$Z_{in} + Z_o\left(\frac{Z_o+Z_L \coth \gamma L}{Z_L+Z_o \coth \gamma L}\right) = Z_o\left(\frac{Z_o \sinh \gamma L + Z_L \cosh \gamma L}{Z_L \sinh \gamma L + Z_o \cosh \gamma L}\right)$$

### (b) Insertion Loss

When the source and load are connected directly, the current which flows in the load is:

$$i_s = \frac{E}{Z_s + Z_L}$$

With an intervening line the appropriate loop equations are:

$$E = i(Z_s + Z_A) + i_L(Z_A + Z_L)$$

$$0 = -i \ Z_B + i_L(Z_A + Z_B + Z_L)$$

Therefore the current loss ratio is

$$\frac{i_L}{i_s} = \underline{Z_s+Z_L}. \quad \frac{E \ Z_B}{Z_A \ Z_s + Z_B \ Z_s + Z_L \ Z_s + Z_A^2 + 2Z_A \ Z_B + Z_A \ Z_L + Z_B \ Z_L}$$

$$= \frac{Z_o(Z_s + Z_L)}{Z_o(Z_s + Z_L) \cosh \gamma L + (Z_L \ Z_s + Z_o^2) \sinh \gamma L}$$

Hence the insertion loss of the line facility is

$$\text{Insertion Loss} = 20 \log \left| \cosh \gamma L + \sinh \gamma L \left( \frac{Z_L Z_s + Z_o^2}{Z_s Z_o + Z_L Z_o} \right) \right| \text{ db} \qquad (24)$$

3. <u>Terminal Impedance Connected to Line Through a Transformer</u>

The equivalent circuit for the case in which the office is connected to the line through a transformer of turns ratio 1:n is shown in Figure 26.

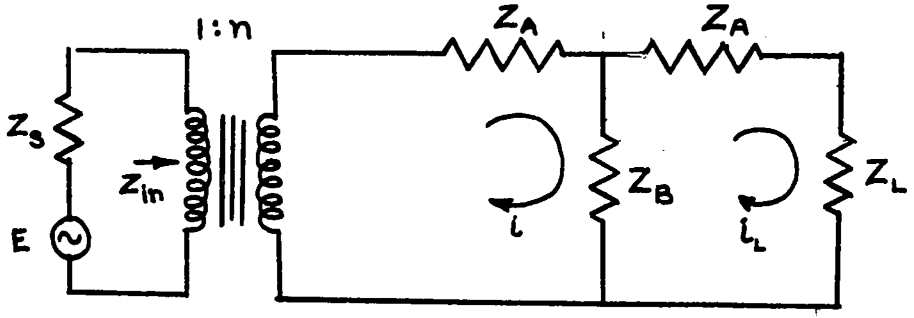


FIGURE 26

EQUIVALENT CIRCUIT OF A HOMOGENEOUS TRANSMISSION LINE
WITH TRANSFORMER CONNECTION

By comparison with equation (23)

$$Z_{in} = n^{1/2} Z_o \left( \frac{Z_o \sinh \gamma L + Z_L \cosh \gamma L}{Z_L \sinh \gamma L + Z_o \cosh \gamma L} \right) \qquad (25)$$

The appropriate loop equations for Figure 26 are:

$$nE = i(n^2 Z_s + Z_A) + i_L(Z_A + Z_L)$$

$$0 = -iZ_B + i_L(Z_A + Z_B + Z_L)$$

From which the current loss ratio is

$$\frac{i_L}{i_s} = \frac{Z_s + Z_L}{E} \cdot \frac{nE\ Z_B}{n^2 Z_A Z_s + n^2 Z_B Z_s + n^2 Z_L Z_s + Z_A{}^2 + 2Z_A Z_B + Z_A Z_L + Z_B Z_L}$$

$$= \frac{}{Z_o(n^2 Z_s + Z_L) \cosh \gamma L + (n^2 Z_L Z_s + Z_o{}^2) \sinh \gamma L}$$

Hence the insertion loss of the facility is

$$\text{Insertion Loss} = 20 \log \quad \frac{n^2 Z_s + Z_L}{n(Z_s + Z_L)} \cosh \gamma L + \frac{n^2 Z_L Z_s + Z_o{}^2}{n\ Z_o(Z_s + Z_L)} \sinh \gamma L \qquad (26)$$