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Studies of Telephone Line Wire Spacing Problems

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By spacing a wire and its mate closer than has been the usual custom, and thus obtaining a greater separation between pairs on open wire telephone lines, inductive interference can be diminished and higher carrier frequencies transmitted, thus increasing the message carrying capacity. The hazard of the wires swinging into contact in the wind is controlling in the selection of a minimum spacing. This article gives the results of studies made to determine the effect of natural winds on variously spaced and arranged wires suspended in accordance with telephone practice.

UNTIL recent years, it has been the usual practice in the Bell System to use a spacing of 12 inches between adjacent wires on a crossarm with the exception of the wires of the pole pair which are more widely separated to provide climbing space. By reducing this 12-inch spacing between the wires of non-pole pairs and obtaining a correspondingly greater separation of pairs, a decrease is obtained in the crosstalk coupling between pairs and also in the induced voltage from such external sources as radio stations and static. This permits the transmission of higher carrier frequencies and provides a greater number of communication channels without impairing the quality of transmission. The increased number of channels that can be obtained is a function, among other factors, of the magnitude of the change in wire spacing.

It was with a view to ascertaining the limitations that might be imposed upon such a rearrangement of the wires through their swinging into contact in winds that the study herein described was initiated by Bell Telephone Laboratories.

It is interesting to note here that, since the early results of this study became available, about 75,000 pair-miles of toll line wire have been installed with an 8-inch spacing between the wires of a pair and recently some 2,600 pair-miles with a 6-inch spacing between the wires of a pair.

At the outset of this study, considerable thought was given to a theoretical determination of the limiting factor or the chance of two parallel wires contacting in the wind, but with little success. Difficulty was encountered in taking into consideration some of the factors involved, principally the gusty nature of the winds to which a pole line is frequently subjected. There was evolved out of this attack, however, a theory embodying the movements of a single suspended wire in wind. This theory, which was presented in a previous article,[1] contributed to the general knowledge of wire movements in wind and gave information on the equilibrium position of a span of wire in a steady wind and the movements of the wire about this position with gusts of wind superimposed on this steady wind. This theory is referred to later.

As important as this theory is, it did not solve the problem of determining the chances of two parallel wires swinging together in natural winds. Consideration was also given to the possibility of obtaining this information through tests of model lines in a wind tunnel. While the problem of meeting the requirements of dynamic similarity in these model tests did not appear to offer serious trouble, the problem of simulating natural wind conditions did present difficulties of major proportions. The line of approach finally adopted was a full scale test of variously spaced and arranged wires on lines erected at a location especially selected for its unusual exposure to natural winds.

This site which is in the township of Chester, New Jersey, is about 950 feet above mean sea level. It is the highest point for many miles in every direction and is particularly well exposed to the prevailing winds which are northwest in this locality.

Provision of Test Facilities

On this site there was first erected a six span line, referred to herein as Line 1, in a direction as nearly perpendicular to the prevailing northwest winds as the contour of the ground would permit without excessive pole heights at the extremities. The span between poles was 130 feet, the Bell System standard length for heavy open wire lines, except at the ends where two poles were set a few feet apart in line for convenience in testing. Figure 1 gives a view of the line and Fig. 2 the special end construction. This arrangement made it possible to include span lengths of 130 and 260 feet in any test. The latter span length was obtained by attaching the wires to the lower

[1] "Motion of Telephone Wires in Wind," D. A. Quarles, *Bell System Technical Journal*, April 1930.

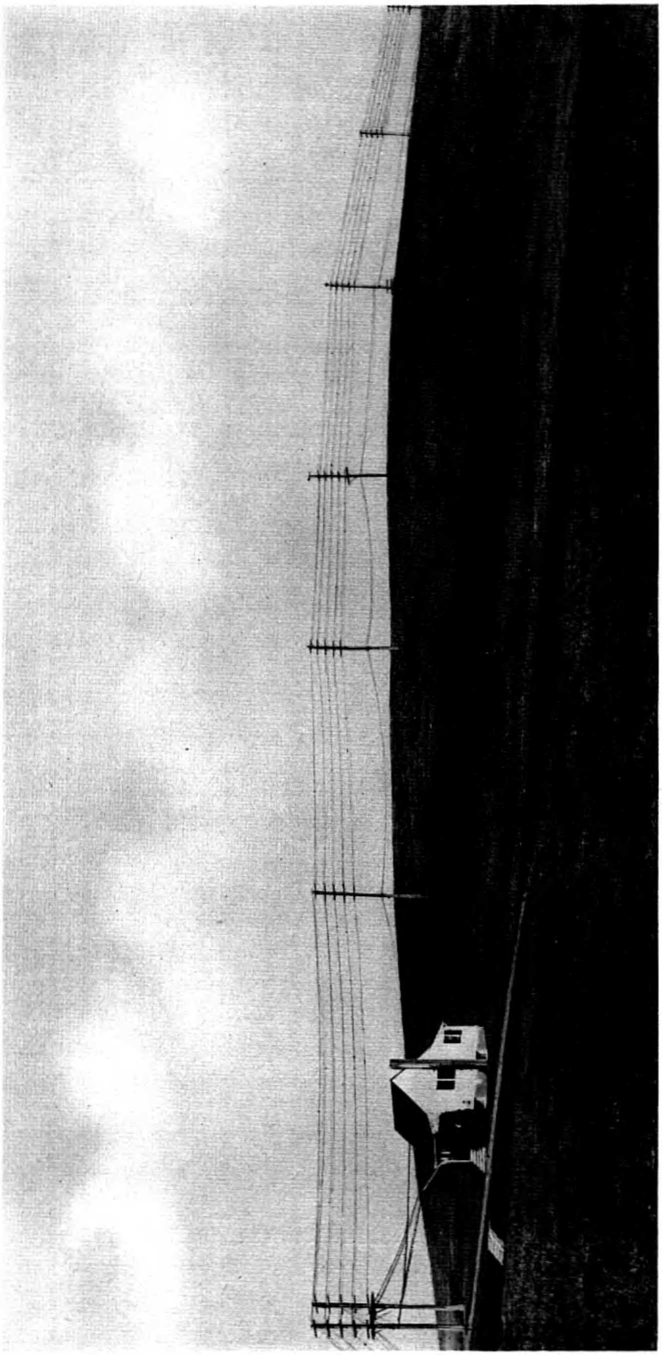


Fig. 1—Line 1 and test house at Chester, New Jersey.

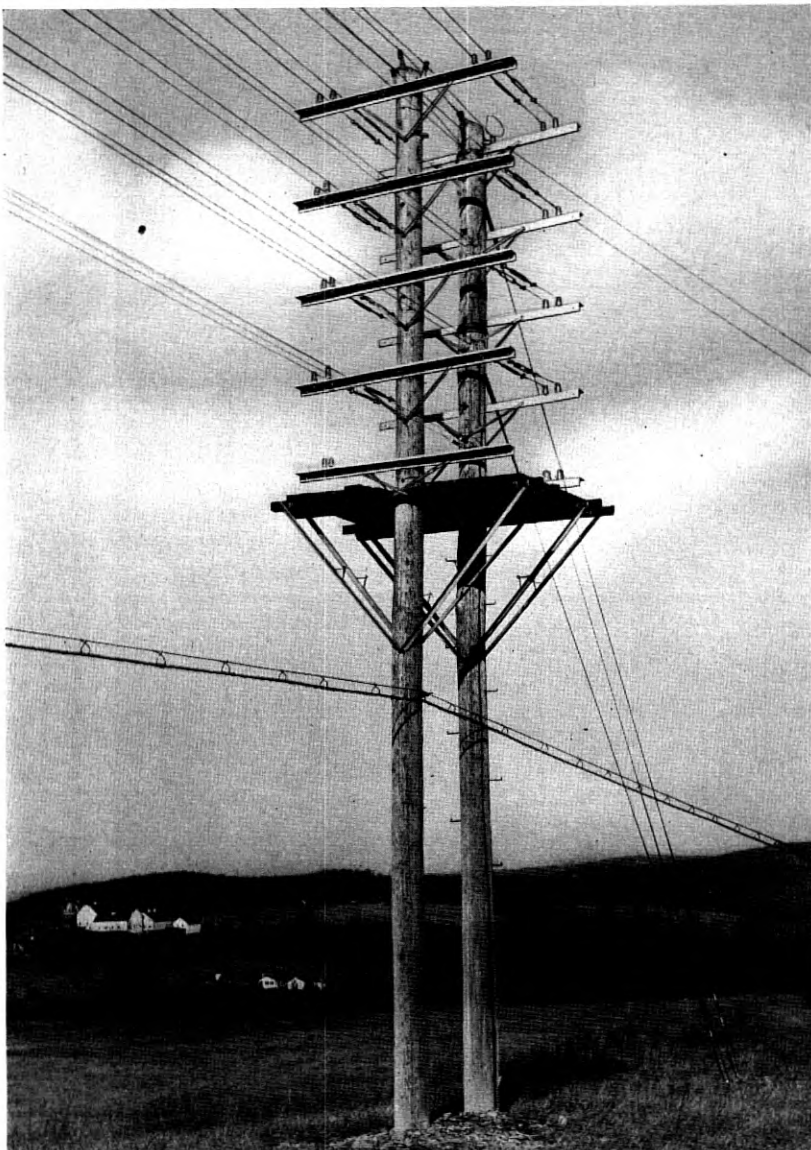


Fig. 2—Double pole construction at end of Line 1.

crossarms at alternate poles. Later another line (Line 2) was erected. This line consisted of three spans, one each of 100, 160 and 260 feet.

Special steel crossarms were mounted on each pole with a vertical separation between them somewhat greater than the two feet usually used in the Bell System. This was to lessen the effect of wind shielding on the test results. These steel crossarms were slotted so as to accommodate steel insulator pins and make it possible to vary the spacing at will. On each pole of Line 1 were mounted five of these crossarms each carrying eight pins, two pairs on each side of the pole. The line wires used were hard drawn copper, 0.104 inch and 0.165 inch in diameter. These sizes comprise the two extremes of the three sizes of copper line wire most frequently used in the Bell System, the intermediate size being 0.128 inch in diameter. As the results obtained during the first two years indicated that the size of wire, within the range of interest, did not appreciably affect the contacting tendency, later tests were confined to the 0.165-inch diameter wire which was selected because of its relatively greater use for important circuits. On Line 2, one crossarm with four pairs of 0.165-inch diameter wire was mounted in the 260-foot span and two crossarms of the same size wire in the 100- and 160-foot spans.

The spacings used in the tests between the wires of a pair comprised 3, 4, 6, 8 and 12 inches, a range which starts with as small a horizontal spacing as appeared to offer possibilities, with the present type of construction, and extends up to the previous standard of 12 inches. The sags used conformed to Bell System Practices and ranged from 4 inches to 45 inches depending upon temperature and span length. In certain of the tests sag inequalities between the wires of a pair were introduced to simulate chance conditions. In referring to the results unless otherwise noted it is to be understood that the two wires of a pair were at equal sags. When the sags in the wires were unequal it is so stated. The amount of the inequality used in spans of 100, 130 and 160 feet was 3 inches at 60° F., while that used in 260-foot spans was 6 inches at 60° F. In these tests the greater sag was always placed in the windward wire while the sag in the leeward wire was maintained so as to conform to Bell System Practices.

In the later stages of the tests certain anti-contacting devices as hereafter described were applied to the wires in the narrow spaced arrangements to raise the velocities at which contacting began.

Recording Apparatus

Apparatus was installed in a building adjacent to one end of the line to record graphically the number and time of occurrence of the swinging contacts between the wires of each pair under test and simultaneously to record the velocity and direction of the wind.

To obtain an idea of the nature of a contact, oscillograph studies were conducted at the outset. The oscillograms (Fig. 3) are representative of the results obtained. The timing wave has a frequency of 60 cycles. When swinging into contact, it appears that the wires scrape and chatter as evidenced by the rapid variations in the current flow. It was found in these oscillograph studies that during a single contact the resistance might vary from zero to 50,000 ohms while in another case the variation might be from zero to 5,000 ohms. The duration of a contact varied approximately from 0.004 to 0.230 second.

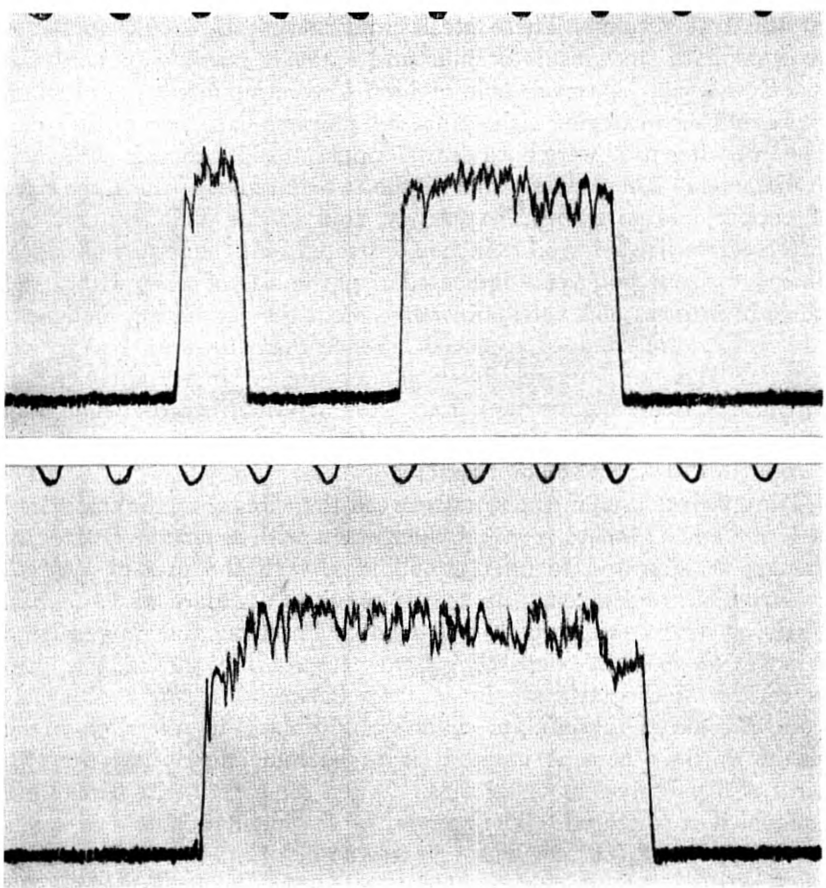


Fig. 3—Oscillograms of swinging wire contacts.

However, the recording apparatus was designed to record a contact that would affect telegraph transmission, which mode of communication was considered to be more sensitive to this type of interference than any other form of transmitted signal. This contact was defined as having a minimum duration of 0.01 second and a resistance of 20,000 ohms or less. The voltage applied to the lines during the test was 260. This voltage was the highest that would obtain on an open wire d-c. telegraph line and would occur when one side of the circuit had a potential of minus 130 volts and the other side plus 130 volts.

Considerable study was given to the selection of apparatus for recording wind velocities. After studying the various types of available instruments and consulting with the United States Weather Bureau, a Burton type of anemometer associated with an Esterline-Angus graphic recorder was selected as best meeting our requirements. This anemometer assembly comprised a four-cup anemometer with the armature of a magneto mounted on the cup-shaft. The magneto current which varies with the rotational speed of the cups was recorded on a milliammeter specially designed for the purpose. This recording milliammeter had several chart speeds so that considerable detail in the velocity change could be obtained when required. The instrument was calibrated to read directly the instantaneous velocity of the wind. A wind vane which registered sixteen directions of wind provided a continuous record of wind direction on the same chart with the wind velocity. The mounted anemometer and the wind vane are shown in Figs. 4 and 5, respectively.

It was realized in selecting such a velocity recorder that our records would not be directly comparable to the weather bureau records which are five-minute average velocities rather than instantaneous velocities unless relations between the two could be established. For this reason when analyzing the wind velocity charts two velocities were read, namely the average and the maximum for each five-minute interval. To further the comparison it was established that the maximum instantaneous velocity ranged greater than the five-minute average velocity by an average figure of 1.4 for velocities greater than 15 miles per hour. This figure which applies to the Chester location and the Burton instrument was obtained by taking the average ratio of the maximum velocities to the five-minute average velocities for 500 cases. Figure 6 shows the frequency distribution of these 500 cases. This graph indicates that the modal value of the ratio as well as the arithmetic mean is approximately equal to 1.40. Two-thirds of these cases fall between ratio values of 1.25 and 1.55.

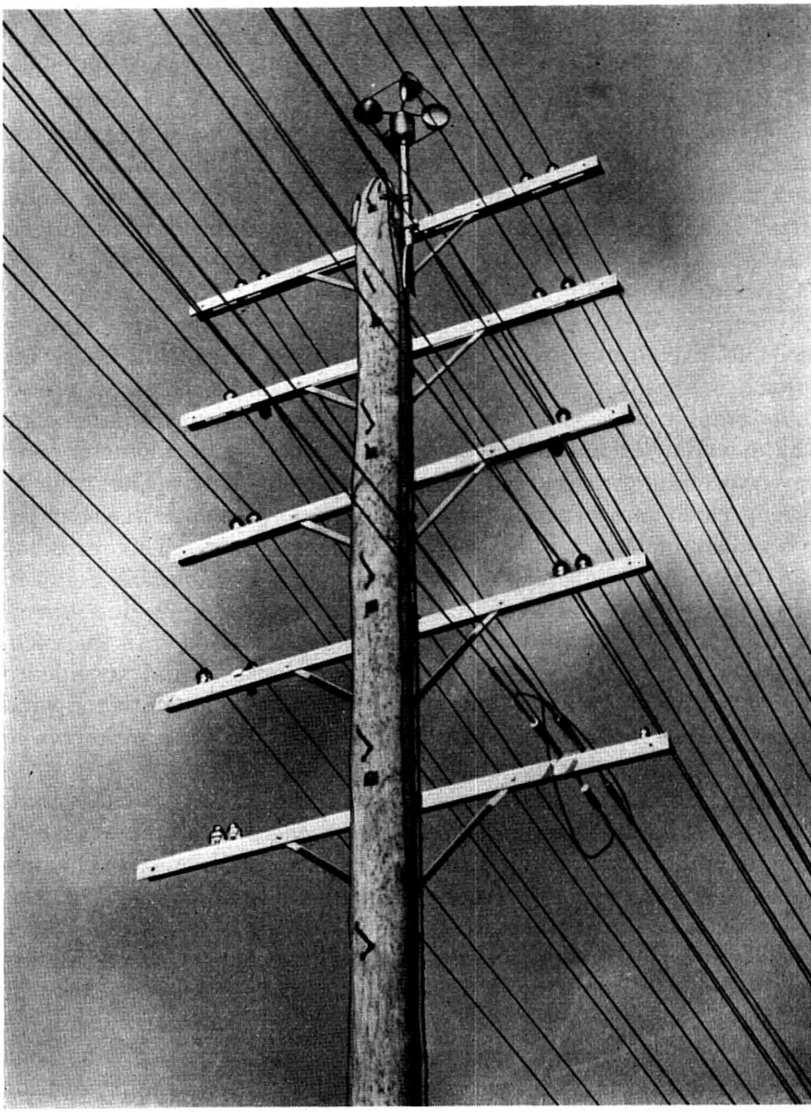


Fig. 4—Cup anemometer mounted on pole of Line 1.

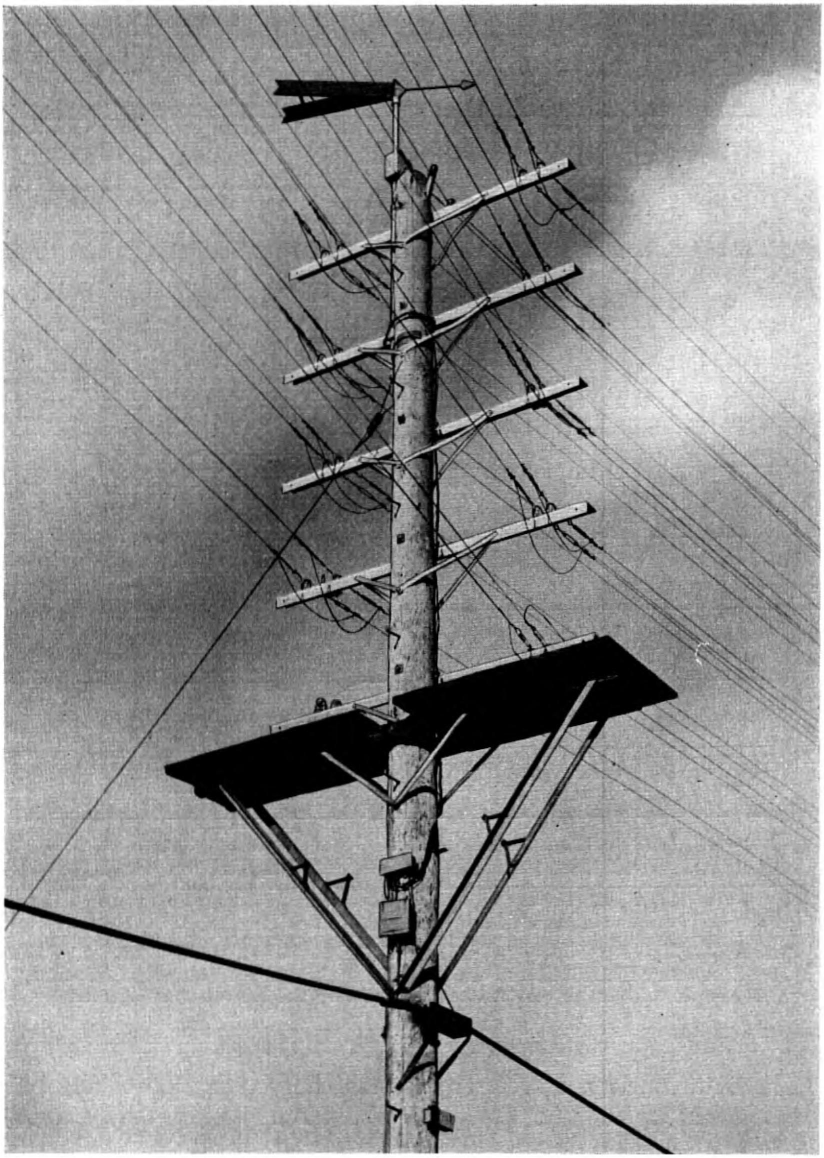


Fig. 5—Wind vane mounted on pole of Line 1.

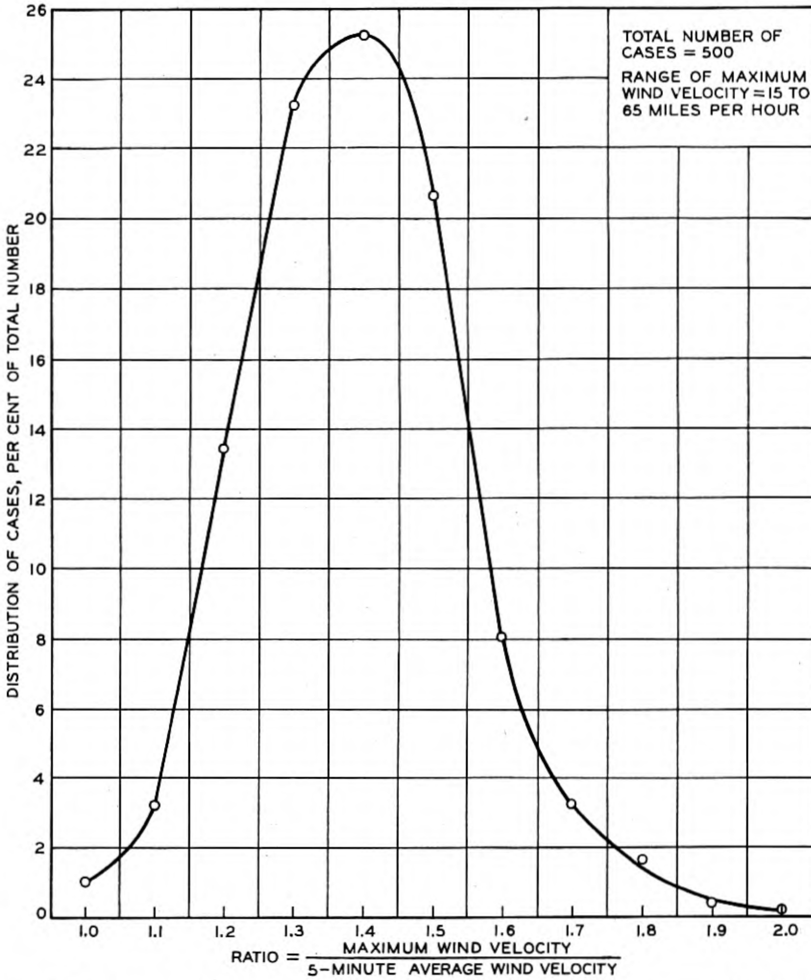


Fig. 6—Frequency distribution of the ratios of maximum instantaneous velocities to five-minute average velocities as recorded by the Burton anemometer.

Method of Treating Data

The data considered necessary for the characterization of any pair arrangement were:

1. The number of contacts.
2. The simultaneous velocity and direction of the wind.
3. The sags of the wires.
4. The air temperature (because of its effect on wire sag).
5. The weather, particularly the presence or absence of glaze.

To simplify to some extent the long process of correlation and analysis, first, the velocities recorded at 16 directions to the line were converted to normal velocities, which should be borne in mind in considering the results. This conversion was made by multiplying the recorded velocities by the cosine of the angle between the normal to the line and the true direction of the wind. The propriety of taking this step was based on appropriate wind tunnel tests made at New York University and reported in the *Bell System Technical Journal.*[2] From this point on the data were classified according to the procedure outlined in Fig. 7.

This procedure provided a history of the contacting on each pair arrangement tested. This history detailed the number of contacts occurring in each five-mile-per-hour cell of maximum and five-minute average normal wind velocity for each division of sag. Each division of sag comprised a cell of one to three inches depending upon the length of span.

These results were analyzed with the view of determining first, the instantaneous velocity, at which contacting begins to occur for each pair arrangement, and second, any relationships existing between the fundamental factors of spacing, sag, span length and such instantaneous velocities which are hereinafter referred to as threshold velocities. The term "threshold velocity" as used in this article does not relate to the five-minute average velocities but to the maximum velocities previously mentioned. To express threshold velocities in terms of five-minute average velocities it is necessary to divide by the factor of 1.4, referred to above.

The analysis of the data directed towards determining the first objective or the threshold velocity for each pair arrangement revealed considerable variation in the magnitudes of these velocities for any particular sag. This has been ascribed to the variability of natural winds. Under these conditions it appeared to be appropriate to select the velocity most frequently associated with the beginning of contacting as the threshold velocity for a given arrangement at the prevailing sag. Thus the modal value was taken as the threshold velocity, or the nearest velocity when expressed in multiples of five miles per hour to the true modal value. The accompanying Table I lists the threshold velocities for the arrangements tested.

Regarding the second objective, namely, the analysis of the data for the purpose of determining relationships existing between the fundamental factors of spacing, span length, sag and wind velocity,

[2] "Forces of Oblique Winds on Telephone Wires," J. A. Carr, *Bell System Technical Journal*, October 1936.

Method of classifying data for analysis

- Glaze absent
  - Span length
    - 100′
    - 130′
    - 160′
    - 260′
    - From here each span length is treated as the 260′ span, shown.
      - Type of pair arrangement
        - #1 (4″ spacing)
          - Equal* sag
            - Sag division
              - #1
                - Maximum normal wind velocity
                  - Number of 5-minute periods the wind is in each velocity cell (0 to 5, 6 to 10, etc. m.p.h.) and number of contacts in each period.
                - 5-minute average normal wind velocity
                  - This is treated the same as the maximum normal wind velocity.
              - #2
              - #3
              - #4
              - #5 etc. (See sag table at right)
              - From here each sag division is treated as sag division #1, shown.
          - Unequal† sag
            - From here unequal sag is treated as equal sag, shown.
        - #2
        - #3
        - #4
        - #5 etc.
        - From here each pair arrangement is treated as pair #1, shown.
- Glaze present
  - Radial thickness of glaze
    - 0.1″
    - 0.2″
    - 0.3″
    - 0.4″
    - 0.5″ etc.
    - From here each radial thickness of glaze is classified in the same manner as in the case of "glaze absent."

Table of sags (inches) from Bell System Practices G31.115

Sag division	1	2	3	4	5	6	7	8	9	10	11
Temp. ° F.	0	10	20	30	40	50	60	70	80	90	100
Span (feet) 100	3.5	3.5	4	4	5	5.5	6	6.5	7.5	8.5	9.5
130	5.5	6	6.5	7	8.5	9	10	11.5	12.5	14	16
160	9	9.5	10.5	11.5	12.5	14	15	16	18	19.5	21
260	25.5	27.5	30	32	34.5	37.5	40	43	46	49	52

* Equal sag—Both wires of the pair were maintained at the sag given in Bell System Practices G31.115.

† Unequal sag—The wire away from the prevailing winds was maintained at the sag given in Bell System Practices G31.115 while the windward wire had a greater sag by an amount based on a figure of 3 inches at 60° F. for the 100, the 130, and the 160-foot spans and 6 inches at 60° F. for the 260-foot span.

Fig. 7—Manner in which data were classified for analysis.

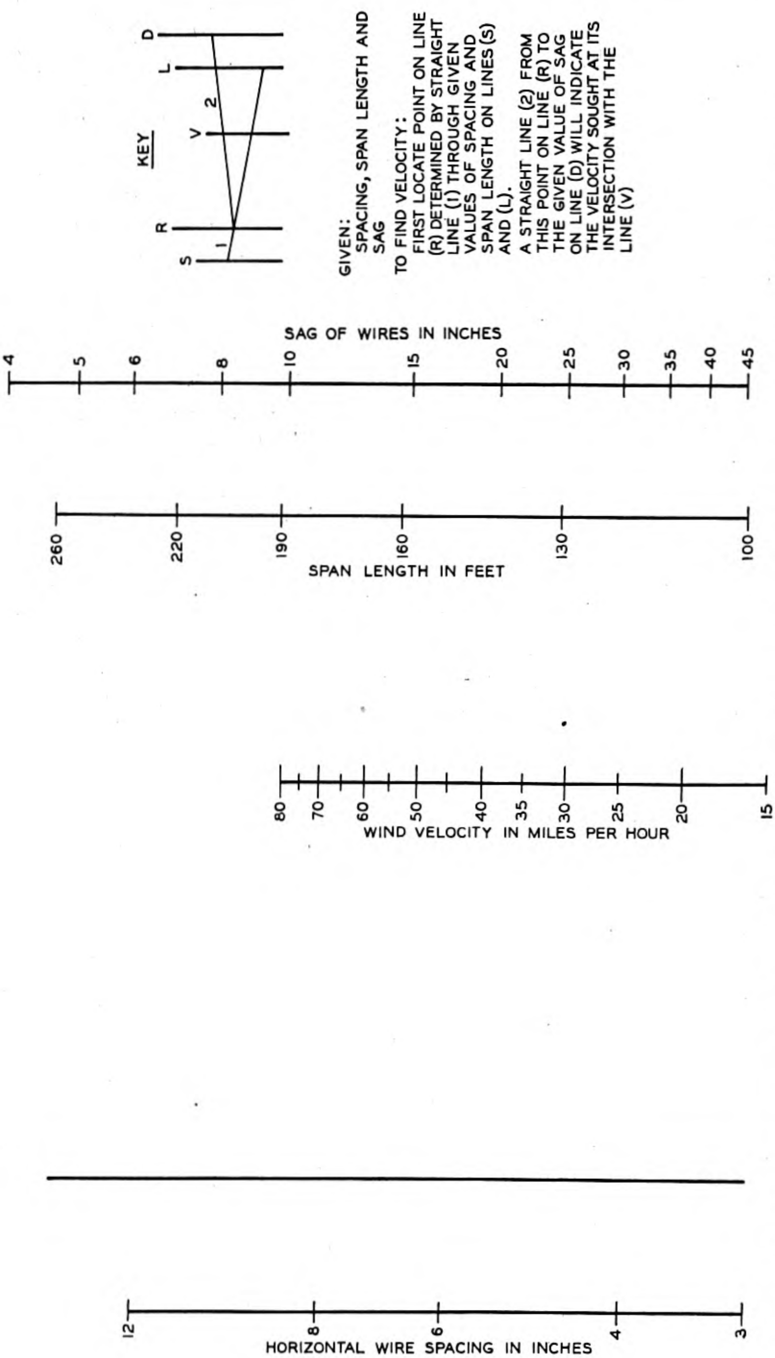


Fig. 8—Nomogram for determining wind velocity (threshold) normal to the line at which wires of a pair begin to contact.

only a moderate degree of success was obtained. From an examination of the data in Table I, it appears for the condition "Equal Sag" that threshold velocities increase with the spacing between the wires and the span length and decrease with an increase in the sag. Because large sags usually accompany long spans it may be somewhat difficult to appreciate the fact that the threshold velocities increase with span length. This is a fact, however, when sag and wire spacing remain constant. Using this basic relation an empirical equation (5) has been developed from the data obtained and is given in Appendix II. A nomogram was constructed for this equation (5) and is given in Fig. 8.

Results of Natural Wind Tests

In Fig. 9 are given two curves of the wind velocities recorded at Chester, New Jersey, during the first seven of the eight years the test was in progress. One of the curves (marked, "Maximum") gives the average annual frequency of occurrence in terms of five-minute periods of maximum wind velocities grouped in cells of five miles per hour. The other curve gives the corresponding data for the five-minute average wind velocities. The maximum velocity reached 60 miles per hour on several occasions each year and exceeded 70 miles per hour on at least one occasion. The velocities occurring during the test are considered to be as great as or greater than those to which the structural plant is usually subjected.

Regarding the data obtained during the presence of glaze, wires with the spacings and sags tested contacted at velocities as low as 10 to 15 miles per hour. To some extent the number of contacts increased with the amount of glaze and the velocity of the wind. Also, generally, a greater number of contacts occurred on the more closely spaced wires than on those with greater spacings. In cases of wires spaced 3 and 4 inches apart there were occasions when they contacted and froze together for periods of several hours. Due to the erratic action of the wires during the presence of glaze not all of these data were classified in detail as were the results obtained when glaze was absent.

The classified data obtained during the absence of glaze in terms of normal threshold wind velocities (maximum) are given in Table I for all the arrangements tested, approximately eighty-five. The data given in this table were collected over a period of approximately eight years. While none of the arrangements were under test over the whole period, all were under test for at least one winter season during these eight years. Since the higher velocities occurred more frequently in the winter than in the summer most of the threshold velocity data

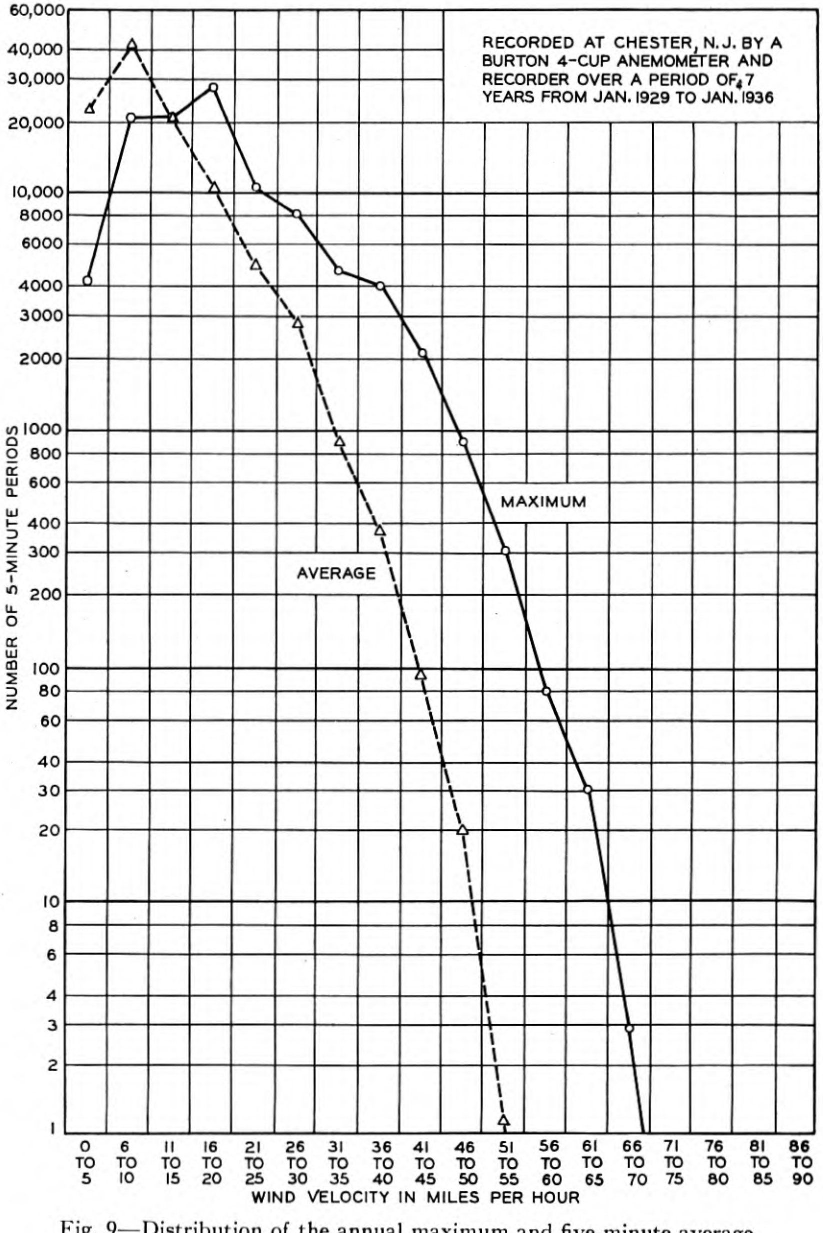


Fig. 9—Distribution of the annual maximum and five-minute average wind velocities.

TABLE I

WIND VELOCITY * (THRESHOLD) NORMAL TO THE LINE AT WHICH WIRES OF A PAIR BEGIN TO CONTACT **
JAN. 1, 1929 TO MAY 1, 1936

100-Foot Span [1]

Equal Sag [2]

Type of Circuit	Temp. °F. 20 / Sag—Inches 4.0	30 / 4.0	40 / 5.0	50 / 5.5	60 / 6.0	70 / 6.5	80 / 7.5	90 / 8.5
3″ Spacing, Unequipped Wires		>60		50	50		45	40
4″ " " "		>60		>60	60		>55	45
6″ " " "		>60		>60	—		—	—
8″ " " "		>60		>60	—		—	—
3″ Spacing, 1–3″ Diam. Disc				—	55	—		
3″ " 1–4″ " "				>65	—	—		
4″ " 1–4″ " "				>65	—	65		

Unequal Sag [2]

Type of Circuit	Temp. °F. 20 / Sag—Inches 4.0	30 / 4.0	40 / 5.0	50 / 5.5	60 / 6.0	70 / 6.5
3″ Spacing, Unequipped Wires	40	35	—			35
4″ " " "	45	40	40			40
3″ Spacing, 1–4″ Diam. Disc			55			
4″ " 1–4″ " "			60			

130-Foot Span [1]

Equal Sag [2]

Type of Circuit	Temp. °F. 20 / Sag—Inches 6.5	30 / 7.0	40 / 8.5	50 / 9.0	60 / 10.0	70 / 11.5	80 / 12.5	90 / 14.0	100 / 16.0
3″ Spacing, Unequipped Wires	40		40	40	—	30	30	30	—
4″ " " "	50		45	40	40	35	—	35	30
6″ " " "	70		>60	>60	55	50	45	45	40
8″ " " "	>70		—	—	—	—	>70	—	>70
12″ " " "	—		—	—	>70	—	—	>70	—
3″ Spacing, 1–3″ Diam. Disc	40				35			35	
" " 2–3″ " "	—				40			40	
" " 3–3″ " "	50				40			40	
" " 1–4″ " "	55	55		45	40	40		40	
" " 2–4″ " "	—	—		—	>65	—		>45	
" " 3–4″ " "	—	—		—	>50	—		>45	
4″ " 1–3″ " "	50				45			45	
" " 2–3″ " "	—				50			>45	
" " 3–3″ " "	65				65			>45	
" " 1–4″ " "	55	55	50	45	45		45	45	
" " 2–4″ " "	—	—	—	—	50		—	>45	
" " 3–4″ " "	—	—	—	—	>65		—	>45	
6″ " 1–4″ " "								60	

Unequal Sag [2]

Type of Circuit	Temp. °F. 20 / Sag—Inches 6.5	30 / 7.0	40 / 8.5	50 / 9.0	60 / 10.0	70 / 11.5	80 / 12.5	100 / 16.0
3″ Spacing, Unequipped Wires	—	35	—		35		35	
4″ " " "	—	40	—		35		35	
6″ " " "	>50	45	45		—		—	
8″ " " "	—	>65	—		>55		—	
12″ " " "	—	>65	—		>55		—	
3″ Spacing, 1–3″ Diam. Disc		45			—		—	
" " 2–3″ " "		45			45		—	
" " 3–3″ " "		50			45		40	
" " 1–4″ " "		50			45	—	40	30
" " 2–4″ " "		50			50	—	—	—
" " 3–4″ " "		55			—	>50	—	—
4″ " 1–3″ " "		45			—			
" " 2–3″ " "		45			—			
" " 3–3″ " "		50			—			
" " 1–4″ " "		50			40	—	—	40
" " 2–4″ " "		50			50	—	50	—
" " 3–4″ " "		>45			—	>50	45	40
6″ " 1–4″ " "	>50		55					55

160-Foot Span [1]

	Temp. °F. 20 Sag—Inches 10.5	30 11.5	40 12.5	50 14.0	60 15.0	70 16.0	80 18.0
3″ Spacing, Unequipped Wires	40	40	35	30	—	—	
4″ " " "	45	45	40	35	35	—	
6″ " " "	55	50	45	—	—	—	
8″ " " "	—	>55	—	—	—	>55	
3″ Spacing, 1–3″ Diam. Disc	—	—	—		40		
" " 3–3″ " "	—	—	—		60		
" " 1–4″ " "	35	35	35		—		
4″ " 1–4″ " "	>50				—		
" " 3–4″ " "	—				60		
6″ " 1–4″ " "		>55	55				
3″ " 1–3″ Mid-span Insulator (Spacer)	—	55	55	—		50	
4″ Spacing, 1–4″ Mid-span Insulator (Spacer)	>55	>55	60	55		55	

	Temp. °F. 20 Sag—Inches 10.5	30 11.5	40 12.5	50 14.0	60 15.0	70 16.0
6″ Spacing, 1–4″ Diam. Disc			45			

260-Foot Span [1]

	Temp. °F. 20 Sag—Inches 30.0	30 32.0	40 34.5	50 37.5	60 40.0	70 43.0	80 46.0
3″ Spacing, Unequipped Wires	25	25	20	20			
4″ " " "	—	30	25	—			
6″ " " "	45	—	35	—			
3″ Spacing, 2½″ Mid-span Insulator (Spacer)	30	30	35	35		25	25
3″ Spacing, 3″ Mid-span Insulator (Spacer)	—	35	—	35		30	—
4″ Spacing, 3½″ Mid-span Insulator (Spacer)	40	40	40	35		—	
4″ Spacing, 4″ Mid-span Insulator (Spacer)	—	40	—	40		35	

	Temp. °F. 20 Sag—Inches 30.0	30 32.0	40 34.5	50 37.5	60 40.0	70 43.0
4″ Spacing, Unequipped Wires	30		—		25	
6″ " " "	40		40		35	
8″ " " "	60		—		50	
12″ " " "	>65		—		>55	

NOTES.—1. The number of spans used in obtaining these data were as follows: 100-foot span—one span, 130-foot span—six spans, 160-foot span—one span, 260-foot span—one and two spans.

2. All sag figures given in this table conform to Bell System Practices G31.115.
EQUAL SAG—Both wires of each pair were maintained at the sag given in these Bell System Practices.
UNEQUAL SAG—The wire away from the prevailing winds was sagged in accordance with these Bell System Practices while the windward wire had a greater sag by an amount based on a figure of 3 inches at 60° F. for the 100, the 130, and the 160-foot spans and 6 inches at 60° F. for the 260-foot spans.

3. During the early stages of the wire spacing study no appreciable difference was noticed in the contacting tendencies of 0.104 and 0.165 inch diameter hard drawn copper wires and for this reason it was agreed to use 0.165 inch diameter wire in all subsequent tests. All the data given in this table were obtained with 0.165 inch diameter hard drawn copper.

4. The sign " > " indicates that a velocity as high as the figure given has occurred when the wires were at the sag designated without contacts taking place.

5. Mid-span insulator—A rod type insulator of glazed Isolantite secured to the two wires of a pair at mid-span definitely fixing the wire spacing at that point.

6. Disc—An insulating disc spacer of phenol fabric 3 or 4 inches in diameter secured to one wire of a pair, the wire passing through the center and perpendicular to the disc. The number of discs per span is indicated. When one was used it was located at mid-span. When two were used they were both located on the same wire one at one-third span from each cross-arm. The three-disc arrangement comprised the two disc arrangement with a third disc located at mid-span on the other wire of the pair.

7. Unequipped Wires—Wires not equipped with discs or mid-span insulators.

* Average of instantaneous velocities recorded by a Burton 4-cup anemometer and recorder. The instantaneous velocity registered by this instrument is approximately equivalent to 1.4 times the 5-minute average velocity.

** To obtain some information on the effect of the length of line a few of these wire arrangements were installed on an 18-mile line between Mt. Pocono and Scranton, Pa. The results were in general agreement with those given here.

were obtained when the sags in the wires were small. Threshold velocity data for the cases of larger sags were obtained by repeating the test in some instances with the wires so tensioned that in cold weather the sags were equivalent to those ordinarily prevailing in warm weather.

In considering the threshold velocities given in this article and in Table I the relative frequency of occurrence of these velocities has an important bearing upon the amount of contacting to be expected. In Fig. 9 the curve for maximum (comparable to threshold) wind velocities experienced at Chester, shows that for velocities greater than about 20 miles per hour the frequency of occurrence decreases as the velocity is increased. For example, in terms of five-minute periods, winds in a velocity cell of 36 to 40 miles per hour and those of higher velocity have been found to occur approximately twice as frequently as winds in a cell of 41 to 45 miles per hour and higher. Thus, in the vicinity of Chester, a wire arrangement with a threshold velocity of say 40 miles per hour would be expected to be subjected to winds that would cause contacts during approximately twice as many five-minute intervals in a year as an arrangement with a threshold velocity of 45 miles per hour. At higher wind velocities an increase of five miles per hour in the threshold velocity will be attended by a greater per cent reduction in the number of five-minute intervals during which winds of sufficient velocity to cause contacts will occur.

Since these results were obtained from tests using short lines which were relatively rigid as compared to long lines it was thought that this feature should be given consideration by supplementing these tests with a few representative tests on a longer line. Accordingly, advantage was taken of a toll line, in the Pocono Mountains of eastern Pennsylvania, which was to be dismantled and an 18-mile section of the line was equipped with four pairs of wires each with a different spacing. The pairs were connected to a recorder which registered a contact of practically the same definition as the recorder at Chester. Data from this line were recorded for approximately two winter seasons. The results were in substantial agreement with those obtained from the tests at Chester.

Equilibrium Position of a Span of Wire in Natural Winds

With regard to the theory [1] relative to the equilibrium position of a span of wire under the influence of a steady wind, a study was conducted at the Chester site to investigate the applicability of this theory under the varying conditions of natural winds. Owing to the

[1] Loc. cit.

gustiness of natural winds it was apparent that the study would have to be conducted on a statistical basis. The equilibrium position of a span of wire in a steady wind can be defined by the angle between the vertical plane through the supports and the plane of the suspended wire. This angle is given by equation (1) in Appendix I. Briefly, the problem was to determine this angle for a large number of cases over the complete range of natural wind velocities experienced and to determine the degree of agreement between these values and the angle given by the theory for the corresponding steady wind velocities.

A pair of 0.165-inch diameter hard drawn copper wires with a lateral spacing of 16 inches was installed in a 260-foot span with the supports at the same level. The two wires were maintained at equal sags throughout this study. To prevent movements of the pole supports four guys were used on each pole, three 120° apart attached at about two-thirds the height above the ground and a head guy attached at approximately the top of the pole. The wires were approximately normal to the prevailing northwest winds and were located in close proximity to and at approximately the same height as the graphic recording anemometer and wind vane used in the wire spacing study. A Pathé motion picture camera was modified to take a continuous picture of a point (center of span) on each wire. The camera was mounted rigidly directly under the wires at the center of the span. A fine platinum wire was attached to the camera just above the film to provide a fixed zero reference point on the film and a mechanism was provided for synchronizing the wind velocity chart and the motion picture film.

With this equipment the wires were photographed when at rest, with no wind present, and a number of pictures were obtained at various wind velocities ranging from zero to approximately sixty miles per hour. Figure 10 is a photograph of a section of film showing the wire images and the reference line. Examination of the films disclosed that except on rare occasions when the wind velocity was low the wires were continually in motion and the point photographed on each wire was represented by a wavy line.

In most cases, during the occasions when the wires were being photographed, the wind was approximately normal to the line. The variation in the distance of each wire image on the film from the zero reference line (with reference to the distance when the wires were at rest) provided a means of determining the actual horizontal displacement of the wires for any recorded wind velocity through the use of the ratio of the actual spacing between the wires to the spacing between the wire images on the film, equation (2), Appendix I. The angle of

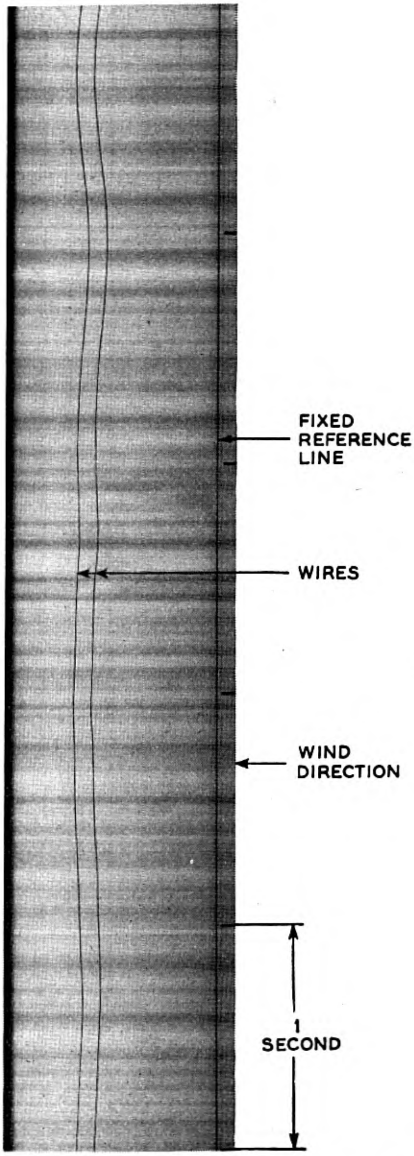


Fig. 10—A photograph of a section of motion picture film showing the transverse movement of wires in wind.

TABLE II

Deflections of Wires in Winds

	Values of α' Computed from Measurements Made on Motion Picture Films—Degrees																		
Transverse Wind Velocity *— M.P.H.	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54
Theoretical Angle, α—Degrees	8.0	10.0	12.0	14.0	16.5	19.0	21.5	24.0	27.0	30.0	33.0	36.0	39.0	41.5	44.5	47.0	49.5	51.5	54.0
	11.5	10.0	11.0	10.0	22.0	20.0	17.5	27.0	23.0	29.0	34.5	47.0	47.5	52.5	52.5	50.0	46.0	38.0	45.0
	12.5	9.5	11.0	9.0	21.0	17.0	21.0	28.0	27.5	46.0	39.5	46.5	51.0	45.5	57.5	46.5	41.5	40.0	41.5
	12.0	8.5	10.0	10.0	19.0	19.0	20.0	26.0	22.0	46.0	47.0	46.5	38.0	44.5	59.0	48.5	41.5	41.5	50.0
	8.5	8.0	10.5	10.5	19.0	21.5	17.5	21.5	22.0	29.5	27.0	44.5	37.0	46.5	41.5	44.5	38.5	33.5	58.0
	8.5	9.0	10.5	17.0	19.5	21.5	26.0	24.0	27.5	32.0	29.5	40.0	38.0	46.5	46.5	35.5	40.5	51.0	59.0
	8.0	7.5	10.5	16.5	11.0	20.5	23.5	29.0	25.5	31.0	29.5	40.0	40.5	48.0	41.5	49.5	42.0	48.5	59.0
	7.0	7.5	9.5	16.5	17.5	10.0	21.5	27.5	24.5	31.0	27.0	46.5	39.0	47.5	45.0	47.5	43.0	58.0	49.5
	11.0	9.0	8.5	17.5	17.5	10.0	22.5	28.5	26.5	29.5	26.5	32.5	37.0	45.0	34.0	45.0	53.0	54.0	40.5
	8.0	9.0	7.5	19.0	17.0	22.0	22.0	22.0	26.0	34.5	26.5	36.0	58.5	41.0	35.0	36.5	46.5	48.5	50.0
	8.5	10.0	12.5	19.0	17.5	19.0	23.0	22.5	29.0	30.0	27.5	37.5	48.0	42.5	41.5	35.5	47.0	46.0	60.5
	7.5	9.5	12.0	18.0	17.0	27.0	20.5	19.5	25.5	31.5	26.5	34.5	33.5	45.0	49.5	51.0	47.5	42.0	51.5
	8.5	9.0	12.0	22.5	16.5	27.0	20.0	21.5	25.5	26.5	36.5	33.5	33.5	45.0	44.5	43.5	46.0	50.5	49.0
	8.5	9.5	10.5	19.5	23.0	27.5	20.5	19.5	23.5	25.0	33.0	42.5	26.5	44.0	45.0	33.0	54.0	42.5	48.5
	7.5	8.0	9.5	18.0	24.0	27.0	26.0	28.5	23.0	25.5	35.5	42.0	27.5	38.0	26.5	27.0	54.5	55.5	55.0
	8.0	8.0	8.5	19.0	22.5	13.5	24.0	26.5	21.0	23.5	33.0	40.5	30.0	38.0	63.5	42.0	56.0	47.5	50.0
	8.0	11.0	8.5	17.0	26.0	13.5	21.0	25.5	21.0	22.5	26.5	37.5	32.0	32.0	67.0	48.5	49.0	49.5	49.0
	7.5	9.0	10.0	17.0	15.0	12.5	23.5	30.0	20.0	23.5	36.0	34.5	29.0	25.0	55.5	61.0	65.0	48.0	52.5
	8.0	9.0	10.0	17.5	13.5	13.5	26.5	26.0	29.0	24.0	33.5	34.0	31.5	28.5	44.0	53.0	54.0	56.0	46.5
	7.0	9.0	9.5	16.5	13.5	10.5	25.5	23.5	21.5	24.5	37.0	37.0	46.0	32.0	52.0	48.0	37.0	59.5	54.5
	8.0	8.0	9.0	16.5	13.5	11.0	22.5	21.0	31.0	22.5	38.5	36.5	51.5	34.5	43.5	47.0	36.0	61.0	49.5
Average Value, $\bar{\alpha}'$	8.7	8.9	10.0	16.3	18.3	18.2	22.2	24.9	24.7	29.4	32.5	39.5	38.8	41.1	47.2	44.6	47.0	48.5	51.0
Standard Deviation, σ'	1.695	0.922	1.332	3.705	4.060	6.283	2.674	3.403	3.169	6.892	5.801	4.976	9.217	7.491	10.325	8.086	7.600	7.661	5.659

* Each wind velocity tabulated represents a 2-mile cell, that is, 20 m.p.h. includes all transverse velocities from 19.1 to 21.0 m.p.h. inclusive.

deflection of the suspended wires from a vertical plane in a natural wind could then be computed, equation (4), Appendix I, since the sine of this angle is equal to the horizontal displacement divided by the stretched sag of the wires. If the supports were assumed to be rigid the stretched sag could be calculated directly through the use of equation (3) in Appendix I. However, despite the precautions taken to prevent movements of the pole supports it was found that the poles would bend when the tension in the wires varied. For this reason the deflection of each pole for various wire tensions was measured and this factor was taken into account in determining the stretched sag. The correction applied to the stretched sag as computed from equation (3) was in some cases as great as three inches. Furthermore since the length of wire varies with temperature the particular temperature at which a picture was taken had to be given consideration in computing the stretched sag.

Following the procedure described above, 20 values of the angle representing the equilibrium position of the wires were obtained for each two-mile-per-hour cell of transverse or normal wind velocity over a range of 17 to 55 miles per hour. The average experimental angle was computed for each velocity cell and the degree of dispersion of the individual values was determined in the regular manner.

Table II gives the values of the angle of deflection of the wires calculated from the experimental data, also the average angle and the best estimate of the true standard deviation for each two-mile-per-hour wind velocity cell. For comparison the theoretical angle of deflection as computed through the use of equation (1) is given for each cell. The maximum and the minimum angles determined experimentally might be plotted versus the theoretical angles, but these data furnish no definite measure of the dispersion since maximum and minimum values depend upon the number of observations made. For this reason the degree of dispersion was determined for single observations and for averages by obtaining an estimate of the true standard deviation which is independent of the number of observations. Figure 11 shows the frequency distribution of the angles determined experimentally and also the "three-sigma" limits for the wind velocity cell of 25.1 to 27.0 miles per hour.

In Fig. 12, the average experimental angle for each velocity cell was plotted against the theoretical angle as given by equation (1) and a regression or trend line was determined for these points. For comparison with this line is given a reference line of exact agreement. The "three-sigma" limits for single observations and for averages of 20 observations, were also plotted against the theoretical angle in

Fig. 12. The standard deviation shows a tendency to increase as the angle of deflection is increased. However, as might be expected from the use of natural winds for the experiments in place of the steady wind

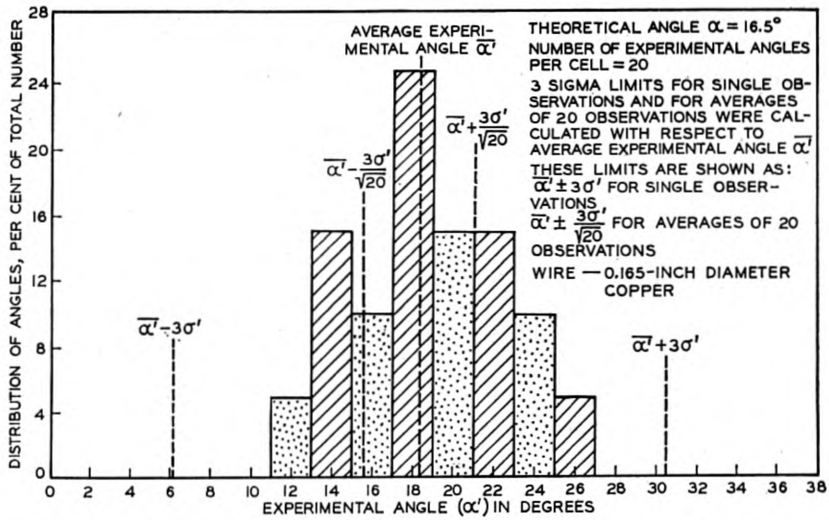


Fig. 11—Distribution of experimental angles of deflection of a suspended wire in a transverse wind velocity cell of 25.1 to 27.0 miles per hour.

assumed in the theory, there was irregularity in the "three-sigma" limits. For this reason a regression line was determined for all the points in each particular "three-sigma" limiting group and the lines were drawn. This graph shows the agreement between the angle of deflection of the wire as determined by the experimental method and that given by the theoretical equation (1). The area between the two extreme limit lines represents approximately the range within which single values determined experimentally would be expected to fall. Likewise, the area between the two inner limit lines represents approximately the range within which averages of 20 values for a particular wind velocity cell would be expected to fall.

In general, the results indicate that the theory for the equilibrium position of a suspended wire under the influence of an assumed steady transverse wind is applicable within reasonable limits to a wire subjected to the varying conditions of natural winds.

An Accelerated Method of Test

Testing the merits of various arrangements in natural winds is a slow procedure in which it is necessary to await the course of nature.

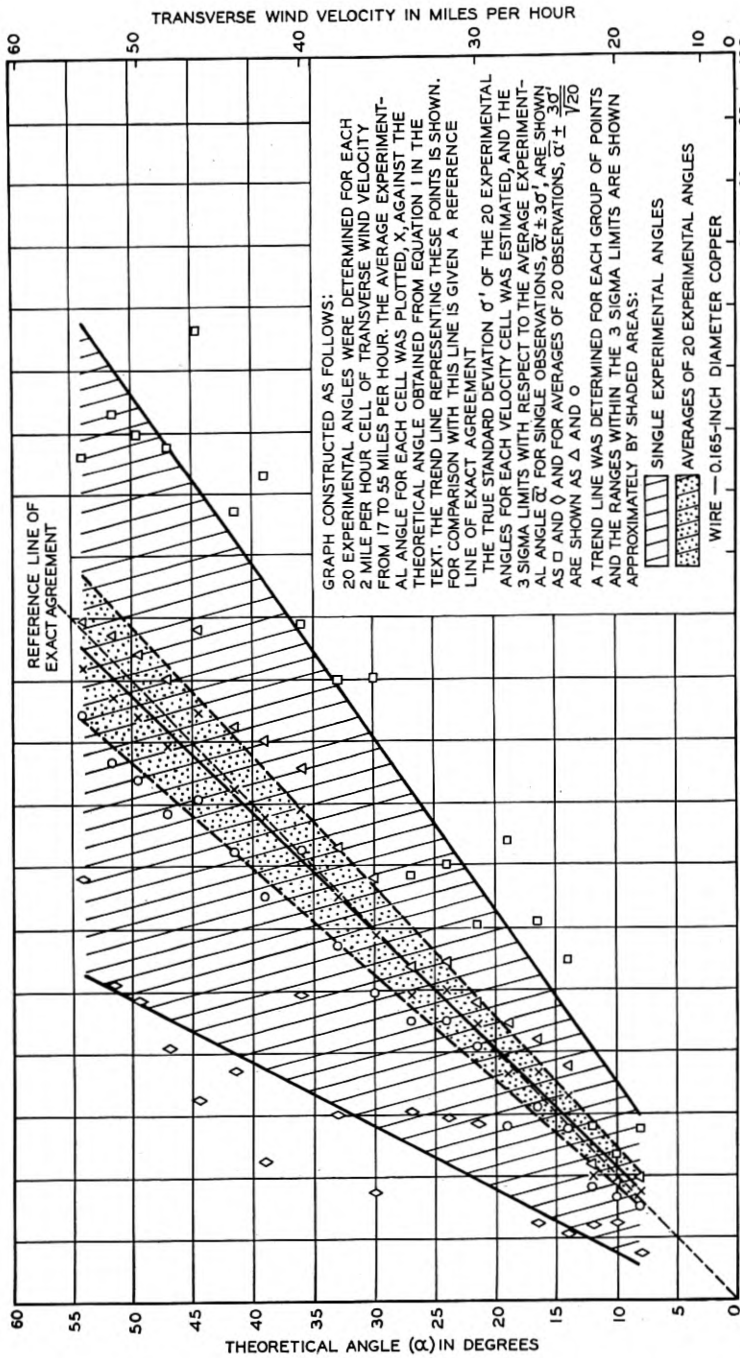


Fig. 12—A comparison of experimental and theoretical angles of deflection of a suspended wire in winds.

In order to narrow the scope of the test in natural winds to the most representative and promising of the various proposed arrangements, an accelerated method of test was used for characterizing the proposals in a preliminary way.

This accelerated method was suggested by the above mentioned theory concerning the equilibrium position of a span of wire in wind. From this theory it was conceived that the relative merits of a type of wire arrangement could be determined by successively deflecting one wire of a pair outward and upward and releasing it to swing towards the other wire through an increasing series of known angles until the two contacted. The theoretical wind velocity corresponding to this minimum angular displacement producing contacts would then be determinable through the use of equation (1).

While it was realized that such a procedure does not simulate the contacting of wires in natural winds, it was thought that from a relative point of view the arrangement requiring the greater angular displacement and therefore the higher theoretical velocity to produce contacting might also require a higher natural wind velocity. Further, it was felt that there was a possibility of being able to determine not only the relative merits of types of arrangements but also their natural wind threshold velocities by correlating the data obtained by the accelerated method with those obtained in the natural wind tests.

Accordingly, a number of tests were made using arrangements on which considerable natural wind data were available. The test set-up comprised a pair of 0.165-inch diameter hard drawn copper wires installed in proximity to the ground with suitable means for changing spacings and sags at will. In order that the deflection of the wire might be accurately controlled and the results reproducible, a series of rods used as guides were mounted rigidly on a vertical support at the center of the span in a plane at right angles to and in proximity to the wires. The points of these rods were positioned in the arc of a circle with a radius equal to the sag in the manually deflected wire. The intervals between the points of the rods in terms of theoretical wind velocity were five miles per hour. The arrangement of rods represented a range of 20 to 80 miles per hour. The test apparatus is shown in the accompanying Fig. 13.

In the first stages of these tests it was found that a pair of wires would not always contact for the same minimum angle of deflection. Experiments showed, however, that during the absence of any natural wind there was a minimum angle for a given wire arrangement which would produce contacting five times in five consecutive trials. This refinement of the method was then adopted and the theoretical velocity equivalent to this angle was termed the accelerated method threshold velocity or the velocity at which contacting begins. It is, therefore, not necessarily the minimum angle or velocity at which the wires can be made to contact but the minimum angle or velocity at which the wires will contact for each of five consecutive trials in practically still air.

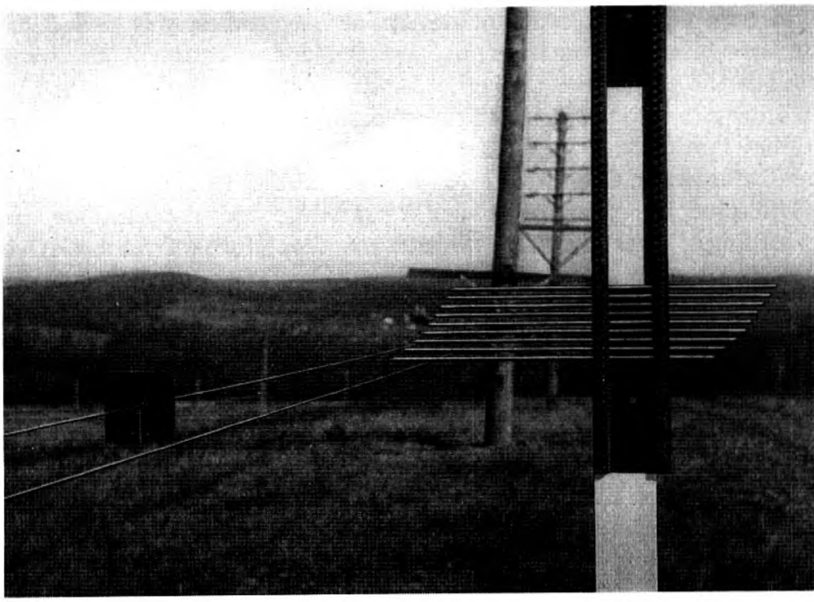


Fig. 13—Apparatus for the accelerated test.

In order that the contacts recorded by the accelerated method should be comparable in definition to those recorded by the natural wind method, the wires used in the accelerated test were connected to the same recording apparatus as was used in the natural wind tests.

From the results obtained through the use of the accelerated method of test an empirical equation was developed for the case of a pair of wires with equal sags. This equation (6) is given in Appendix II. The comparable empirical equation (5) for natural winds, referred to above, is also given in Appendix II. With these two equations it is possible to determine the expected natural wind threshold velocities of a wire arrangement through the use of the accelerated method of test. An equation (7) for this use, which was obtained from the above two equations (5) and (6), is also given in Appendix II.

While empirical equations were developed only for the case of a pair of wires with equal sags, the applicability of the accelerated method is not limited to this case. It was also used where the sags in the two wires of a pair were unequal and, as referred to later, for determining the most promising design of insulating disc (described below) for use in natural wind tests as a means of mitigating the contacting on pairs with the wires spaced, 3, 4 and 6 inches.

Anti-Contacting Insulators

As stated above it was found that wires spaced 3 or 4 inches contacted in wind velocities rather commonly experienced. Some

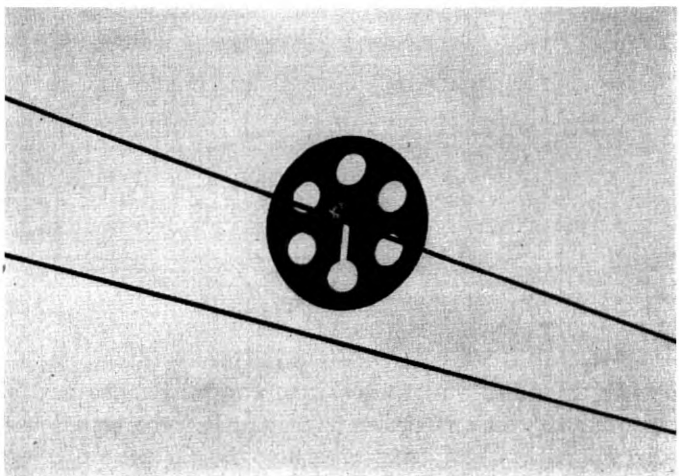


Fig. 14—Insulating disc.

contacting was also recorded on pairs with wires spaced 6 inches. In giving consideration to means of increasing the natural wind threshold velocities of such circuits to those occurring less frequently, two types of anti-contacting insulators were developed. One type, Fig. 14, was a perforated disc of insulating material. When this type was installed on one wire of a pair it was not in contact with the other wire of the pair except when forced there by the action of the wires in wind. The other type, Fig. 15, was a rod-shaped insulating spacer. This spacer bridged the two wires of a pair in the span.

The insulating discs used were 3 and 4 inches in diameter. The arrangements of these discs tested in natural winds comprised one, two or three discs per span per pair of wires. When one disc was used, it was placed at the approximate center of the span on the wire of the pair to the windward side of the line. When two discs were used they were placed on the windward wire at one-third of the distance from each support. The three-disc arrangement comprised the two-disc arrangement with the third disc placed at the center of the span on the other wire of the pair.

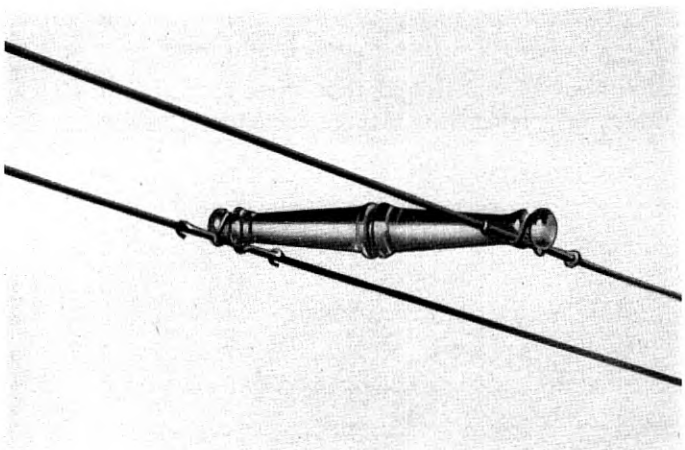


Fig. 15—Insulating spacer.

In selecting the disc and these sizes, various shapes and sizes of insulators (one of which is shown in Fig. 13) were tested using the accelerated method of test referred to above. The circular type was found to give as good results as any other shape and had the advantage of being simple in design.

The insulating spacers were used one per span per pair of wires located at the approximate center of the span. Any insulating spacer bridging the wires of a pair constitutes an additional line leakage path and from this standpoint is undesirable. In this respect the discs have a distinct advantage over the spacers. As stated above, they are not normally in contact with both wires and when such contacts take place they are generally of short duration. Then too, in a long line with wires equipped with discs it is improbable that more than a short section would be affected at one time. The thought was that owing to the additional line leakage provided by the spacers, their use would be confined to the occasional long span and the use of discs to the shorter spans. For this reason the tests involving discs were confined to spans of 160 feet and less and those involving spacers to spans of 160 and 260 feet. The dimensional characteristics of the spacers important from the standpoint of mitigating contacting were tested. These related to the length of the spacer between wires. It was not known whether this distance should be equal to, less than or greater than the spacing between the wires of a pair at the crossarm. The first tests indicated that when this distance was ½ inch greater than the wire spacing, there was a tendency for the pair to roll and the wires to twist around each other. Later tests were confined, therefore, to spacers with a distance between the wires the same as the spacing or ½ inch less. The data obtained in the natural wind tests on wire arrangements where discs and spacers were used are given in Table I.

The effect of insulating discs was to increase the threshold velocities over those for similar arrangements without discs by about 5 to 20 miles per hour. The 4-inch diameter disc has some advantage over the 3-inch diameter disc. Three discs per span or even two discs give results somewhat better than those obtained with a single disc but the gain is relatively slight.

The spacer which holds the wires in the center of the span the same distance apart as the spacing at the crossarm, in general, increased the threshold velocities about 10 to 30 miles per hour for pairs with wire spacings of 3 and 4 inches at equal sags and suspended in spans of 160 and 260 feet over comparable arrangements of unequipped wires. No information is available for the case where the wires of a pair have unequal sags.

The data for the 160-foot span give some comparison between the effectiveness of discs and spacers. In the case of wires spaced 3 inches with one 4-inch diameter disc, contacts occurred at a threshold velocity of 35 miles per hour while the comparable figure for the spacer was 55 miles per hour.

Abstract Conclusion

In these tests typical toll telephone wires were placed in spans of 100, 130, 160 or 260 feet with sags of 4 to 45 inches (depending upon the span length and temperature) and with horizontal spacings between the wires of a pair of 3, 4, 6, 8 or 12 inches. It was found that during the absence of glaze the wind velocities normal to the line when swinging contacts began to occur increased with the wire spacings and also with span lengths (if wire tensions were increased so as to maintain a given sag) and decreased when the sag was increased. An empirical equation based upon this relation and the data (Table I) has been developed for the case of wires at equal sags. As a brief example of the results, in the case of a 130-foot span, it was found that wires spaced 12 or 8 inches were practically free from swinging contacts in wind velocities below about 70 miles per hour, wires spaced 6 inches contacted at velocities around 50 miles per hour and wires spaced 4 or 3 inches contacted at the more common velocities of 30 or 40 miles per hour.

In the absence of glaze, when the wires of a pair were at unequal sags, about 3 inches difference in the 130-foot spans and about 6 inches in the 260-foot spans, there was in general a somewhat greater tendency toward contacting in the shorter spans and a lesser tendency in the longer ones than when the wires were at equal sags.

When glaze was on the wires their action was more erratic and swinging contacts were more general and occurred at lower wind velocities than when glaze was not present.

Regarding the theory [1] relating to the equilibrium position of a suspended wire in a steady wind, tests were conducted at Chester, New Jersey, in which the displacements of a copper wire were photographed in natural winds. It was found that there was general agreement between the angle of deflection of a wire as determined by this theory for a given steady wind and the angle obtained experimentally in a comparable natural wind.

The experimental substantiation of this relationship led to the development of an accelerated method for a quick and economical preliminary classification of various wire arrangements. This method was useful in selecting from among several similar arrangements the most promising ones for test in natural winds. An empirical equation based on the data obtained by the accelerated method for the case of equal sags was developed for expressing the relationship between accelerated method wind velocity, span length, wire spacing and sag. By combining this equation with that developed from the natural wind data a third equation was obtained which was used in determining expected natural wind threshold velocities from the accelerated method results.

In regard to the anti-contacting devices included in the study with the wires spaced 6 inches and less, it was found that:

1. A 4-inch diameter insulating disc placed at the approximate center of the span on one wire of the pair increased the normal wind velocities at which contacting began by 5 to 20 miles per hour over those for the same arrangements unequipped. The use of three discs per span or even two gave an improvement over the use of one but the gain was relatively slight.

[1] Loc. cit.

2. A rod-type insulating spacer used to bridge the wires of a pair in the approximate center of the span was somewhat more effective than one disc, increasing the normal wind velocities at which swinging contacts began by about 10 to 30 miles per hour over those for the same arrangements unequipped.

In general, the higher the threshold velocity, the less frequent will be the occurrence of those winds which will cause contacting. Therefore, if the threshold velocity of a wire arrangement is increased 5 or 10 miles per hour or more by the addition of an anti-contacting device there will be a decrease in the amount of contacting occurring dependent upon the original threshold velocity and the amount of the increase. For example, in the vicinity of Chester, New Jersey, an increase in the threshold velocity of a wire arrangement from 40 to 45 miles per hour results in a reduction of about 50 per cent in the number of five-minute intervals during which winds of sufficient velocity to cause contacts will occur. At higher wind velocities an increase of five miles per hour in the threshold velocity will produce a greater per cent reduction in the number of five-minute intervals during which winds of sufficient velocity to cause contacts will occur.

In regard to the field installations with a spacing of 8 inches between the wires of a pair, referred to at the beginning of this article, no serious difficulties have been encountered except in certain sleet areas where there has been some wrapping and freezing together of the wires. In these locations insulating spacers have been installed on a few pairs and their behavior is being followed. The installations in which a 6-inch spacing has been used have been confined to the warmer sections of the country and no serious trouble has yet been encountered.

APPENDIX I

The expression for determining the angle of deflection or equilibrium position of a suspended wire in a steady transverse wind as given in the theory [1] is

$$\tan \alpha = \frac{kV^2}{mg \cos \gamma}, \tag{1}$$

where α = Angle between the plane of the suspended wire and a vertical plane through the supports,

V = Steady transverse wind velocity (miles per hour),

m = Mass of unit length of wire (slugs),

g = Acceleration of gravity (feet per second per second),

k = Ratio of wind pressure per unit length of wire to square of velocity, and

γ = Angle of inclination of line through supports to the horizontal.

In the study to determine the extent to which this theory would check under the varying conditions of natural winds only the case where $\gamma = 0°$ (both supports at the same level) was considered.

The camera used in this study was equipped with a Tessar F-3.5 lens with a nominal focal length of 40 mm. The films were analyzed with the aid of a motion picture projector. In this projector the film passed over a glass plate on which was engraved a linear scale graduated in hundredths of an inch. The pictures, together with the graduated scale, were projected on to a screen. This method provided a ready means of determining the horizontal displacement of the wire images on the film. The actual wire displacement was then determined through the use of the following relationship:

$$\frac{L_1}{L_2} = \frac{D_1}{D_2}, \tag{2}$$

where L_1 = Distance from wires to camera lens,
L_2 = Distance from camera lens to film,
D_1 = Spacing between wires, and
D_2 = Spacing between wire images on film.

The two wires were maintained at equal sags throughout this study. The equation for determining the stretched sag of a wire if the supports are assumed to be rigid is as follows:

$$a^3 + \frac{3L}{8}(L - R)a = \frac{3wL^4}{64AE}. \tag{3}$$

where a = Stretched sag,
R = Unstressed length of wire,
L = Span length,
A = Cross-sectional area of wire,
E = Modulus of elasticity, and
w = Resultant of wind pressure and gravity components.

As explained in the text, even though the poles were strongly guyed, the supports moved when the tension in the wires varied and corrections were applied to the stretched sag to take account of this movement.

After determining the horizontal displacement and the stretched sag of the wires the experimental angle of deflection (angle of equilibrium position) was calculated by means of the equation:

$$\sin \alpha' = \frac{L_3}{a'}, \tag{4}$$

where L_3 = Horizontal displacement of wires,
a' = Corrected stretched sag of wires, and
α' = Angle of deflection determined experimentally as distinguished from the theoretical angle (α).

The details of the method of determining the equilibrium position of the wires for a particular natural wind velocity were as follows:

> The horizontal displacement of the two wire images on the film at each wave crest and trough was determined. The displacement for the two wire images at each crest and at each trough was averaged. Next the mean displacement on the film of the crest and trough was calculated and also the mean velocity * was determined for this particular time interval. The mean displacement on the film was then converted to actual wire displacement through the use of equation (2) and the experimental angle was determined by equation (4). This average angle was taken as the equilibrium position of the wires for this mean velocity.

APPENDIX II

Empirical Equations

From natural wind tests on arrangements of wires in which both wires of a pair were maintained at equal sags it was found that in the absence of glaze threshold velocities increase with the spacing between the wires and the span length and decrease as the sag increases. An empirical equation obtained from an analysis of the results is as follows:

$$V_w = 22.4\left[\frac{L^{0.1}S^{0.3}}{d^{0.25}}\right]^{2.1}, \tag{5}$$

where V_w = Natural wind threshold velocity (miles per hour),
L = Span length (100 to 260 feet),
S = Wire spacing (3 to 12 inches), and
d = Sag of wires at rest (4 to 45 inches).

The data upon which this equation was based comprised approximately fifty cases where swinging contacts actually occurred. Regarding the degree to which this equation represents these data, there were only about five cases which deviated as much as five miles per hour in terms of threshold velocity and of these only one deviated as much as seven miles per hour. The nomogram given in Fig. 8 was constructed for this equation (5).

* When the direction of the wind was not normal to the line the normal component of the velocity was determined by multiplying the wind velocity by the cosine of the angle between the actual direction of the wind and the normal to the line.[2]

The comparable empirical equation for the accelerated method of test is

$$V_m = \frac{10Y}{1 - 0.692Y}, \tag{6}$$

where

$$Y = \frac{L^{0.05}S^{0.2}}{d^{0.2}},$$

and V_m = Accelerated method threshold velocity.

The other terms are the same as given above. This equation has a degree of accuracy comparable to equation (5).

These two equations, (5) and (6), were combined to form equation (7) which was used to determine expected natural wind threshold velocities from the accelerated method results.

$$V_w = V_m \left[\frac{2.24L^{0.16}S^{0.43}}{d^{0.325}} \right] \left[1 - 0.692 \frac{L^{0.05}S^{0.2}}{d^{0.2}} \right]. \tag{7}$$

The terms in this equation are the same as those given above.

Variable Equalizers

By H. W. BODE

THE use of equalizing structures to compensate for the variation in the phase and attenuation characteristics of transmission lines and other pieces of apparatus is well known in the communication art. Ordinarily, of course, an equalizer has a definite characteristic fixed by the apparatus with which it is to be associated. It may happen, however, that the characteristics demanded of the equalizer cannot be prescribed in advance, either because the characteristics of the associated apparatus are not known with sufficient precision, or because they vary with time. Examples are found in the equalization of transmission lines the exact lengths of which are unknown, or the characteristics of which may be affected by changes in temperature and humidity.

In recent years the problem of providing equalizers which will meet such conditions as these has assumed particular importance because of the large variations in line attenuation which may result from temperature changes in new carrier systems. In some of these the maximum change in attenuation is more than 1 db per mile. Evidently, if a reasonable standard of quality is to be maintained for systems the overall length of which may be several hundred or several thousand miles, these variations must be compensated for with great accuracy. Moreover, since the total amount of correction must necessarily be divided up into much smaller amounts appearing at many points, and since the daily cycle of temperature changes may be large, it is almost essential that the adjustments made be so simple that they can readily be performed automatically by a suitable auxiliary circuit.

The variable equalizers described here are attempts to meet this problem. In order to secure the maximum simplicity it has been assumed that the characteristics of the structure are controlled by a single variable element, which in most cases is a variable resistance. It has also been assumed that the temperature coefficient is known as a function of frequency and that it is the same at all temperatures. What is required, then, is a structure by means of which an arbitrary multiple of a given attenuation characteristic can be introduced into a circuit by changes of a single element.

For purposes of future discussion it is convenient to express this requirement in precise form. If the network functions ideally its loss must be given by an equation of the following type:

$$\theta = F_1(\omega) + F_2(\omega)F_3(R), \tag{1}$$

where R is the variable resistance. The function $F_2(\omega)$ corresponds to the temperature characteristic. It must evidently be under our control. The function $F_1(\omega)$ represents a fixed loss, analogous to that of an ordinary equalizer. It is of less importance since it can always be changed by the addition of separate fixed networks. In several of the structures to be described, however, it also is under our control, so that the networks can be used as combined fixed equalizers and temperature correcting devices. The function $F_3(R)$ expresses merely the calibration of the controlling element with respect to temperature, and its exact form is consequently of minor importance.

It is not difficult to find circuits which function broadly in the manner described by equation (1). In most instances, however, the desired proportionality in the set of variable characteristics is realized only very approximately. A simple circuit, which it is hoped is both a fair and a plausible example, may illustrate the sort of performance to be expected.[1] The structure consists of a condenser in series with a variable resistance, bridged across a resistance circuit, as shown by Fig. 1. For high values of the variable resistance we may anticipate that the attenuation will be low at all frequencies, while at lower values a characteristic rising with frequency should be obtained. The network should then behave much like a radio "tone control." An inspection of the actual characteristics, also shown on Fig. 1, indicates, however, that although this general behavior is in fact obtained, the curves change shape rapidly in every range except that corresponding to high resistances and high frequencies, where they are almost constant.

The distortion exemplified by the curves of Fig. 1 is the greatest obstacle in the design of variable equalizers to satisfy the specifications of equation (1). To a certain extent it is unavoidable. It is easily shown for example, that the transfer admittance from generator to load impedance in any network containing a single variable resistance can be written as

$$Y = \frac{ZY_s + RY_0}{Z + R}, \tag{2}$$

[1] More elaborate circuits have, of course, been devised in the past. Mention should be made in particular of the structure described in U. S. Patent No. 2,019,624, issued to Mr. E. L. Norton. For moderate ranges of variation, the characteristics of this network are somewhat similar to those of the structure exemplified later by Fig. 6. Another method of attack is shown by U. S. Patent No. 2,070,668, issued to Mr. W. R. Lundry.

where R represents this resistance, Z represents the impedance which it faces, and Y_s and Y_0, as the equation implies, are the transfer admittances obtained by short-circuiting and open-circuiting R. It is evident by inspection that log Y, which represents the θ of equation (1), cannot be written in the form which the right-hand side of (1) demands. A certain amount of distortion of the type shown by Fig. 1 must therefore always occur.

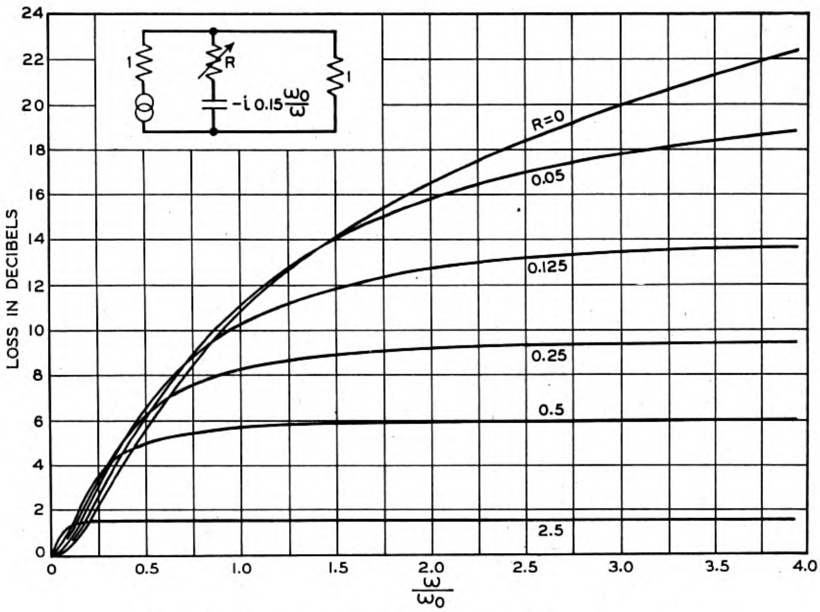


Fig. 1—Characteristics of a simple variable structure.

There still remains the possibility, however, of obtaining a network in which the distortion can be kept within tolerable limits over a given range. The quantities Y_s, Y_0, and Z, which are, of course, all functions of frequency, allow us to determine the transfer admittance at three values of R. The transfer admittances at other settings will then be fixed. If we suppose for simplicity, that the extreme characteristics, corresponding to Y_s and Y_0, are set by the engineering requirements on the structure, the problem reduces to that of so choosing Z in relation to these quantities that the distortion is as small as possible at intermediate settings of R.

Of the variety of possibilities open in the selection of Z, one in particular commends itself by the simplicity and symmetry of the results to which it leads. It is given by the condition

$$Z = \sqrt{\frac{Y_0}{Y_s}} R_0, \tag{3}$$

where R_0 is an arbitrary constant which represents, physically, a reference value for the variable resistance. With the help of this condition (2) becomes

$$Y = \sqrt{Y_0 Y_s} \frac{R_0 + \frac{R}{R_0} Z}{Z + R}, \tag{4}$$

which can be rewritten in a slightly different notation as

$$e^{-\theta} = e^{-\theta_0} \frac{1 + xe^{-\varphi}}{x + e^{-\varphi}}, \tag{5}$$

where $e^{-\theta}$, $e^{-\theta_0}$, x and $e^{-\varphi}$ stand respectively for the quantities Y, $\sqrt{Y_0 Y_s}$, $\frac{R}{R_0}$ and $\frac{Z}{R_0}$.

The significance of the assumption made in equation (3) is apparent from an inspection of equation (5). When $R = R_0$ the total loss θ of the circuit is equal to θ_0. The quantity θ_0 can therefore be described as the average or reference loss of the circuit, corresponding to the average or reference value of R. It is represented by the middle curve shown on Fig. 2. Setting $R = 0$ or $R = \infty$ gives the symmetrically located extreme curves $\theta_0 \pm \varphi$ also shown in the figure. The quantity φ is therefore the extreme change in the attenuation of the network produced by variations in R. Since the two extreme curves correspond to Y_0 and Y_s the situation can also be described by saying that condition (3) fixes the third arbitrary transfer admittance characteristic symmetrically between the first two.

It is easily shown that any other pair of characteristics which correspond to reciprocal values of x, such as those shown by the broken lines in Fig. 2, will also be symmetrically placed with reference to θ_0. This line therefore divides the complete family of characteristics into two equal halves. The departures of the intermediate characteristics from θ_0 are, of course, not strictly proportional to φ. The error can, however, readily be investigated by expanding (5) as a power series in terms of φ.[2] We find

$$\theta = \theta_0 + \frac{x - 1}{x + 1} \varphi + g_3(x) \varphi^3 + g_5(x) \varphi^5 + \cdots, \tag{6}$$

even terms being absent because of the symmetry of the original ex-

[2] A more detailed treatment of this analysis will be found in the writer's U. S. Patent 2,096,027.

pression. The particular forms of the functions $g_3(x)$ and $g_5(x)$ are not of great interest. It is important, however, to know their maximum values, which are respectively 0.03 and 0.002.

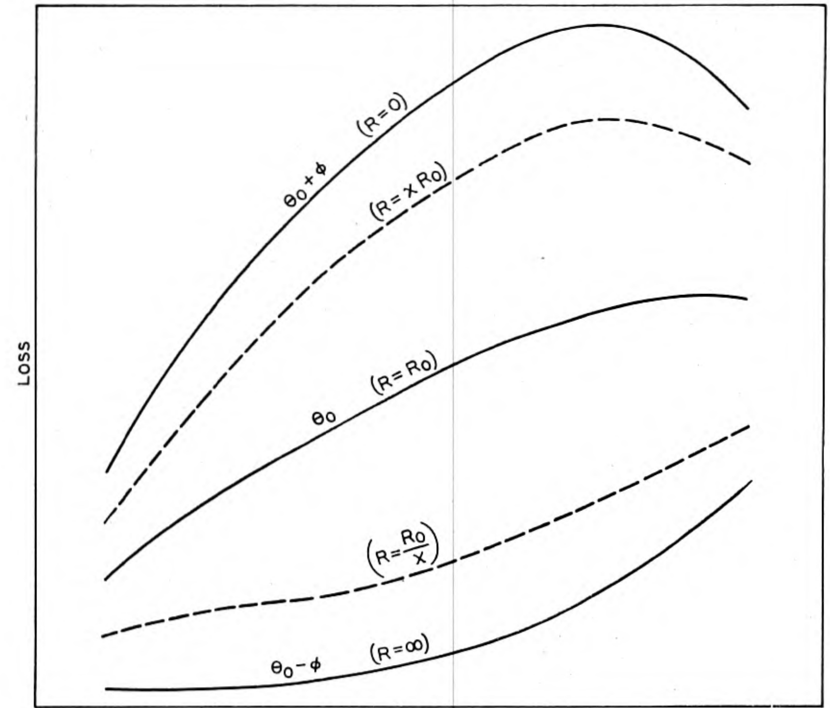


FIG. 2—Diagram to illustrate symmetrical characteristics obtained from the equalizers described in the paper.

The first two terms in equation (6) can evidently be identified with the quantities appearing on the right-hand side of the ideal regulator equation (1). So far as these terms are concerned, the variable characteristics are always strictly proportional to φ. The departure from the ideal is measured by the remaining terms of (6). For ordinary values of φ the series converges so rapidly that only the term in $g_3(x)\varphi^3$ is important. Since the maximum value of $g_3(x)$ is known an estimate of the distortion is easily made, although some allowance is necessary for the possibilities of "splitting differences" in the design process. With the help of these allowances, however, it turns out that the distortion should be about 0.1 db when the maximum value of φ is 1 neper, corresponding to a total variation in attenuation of about

18 db. For other values of φ the distortion is, of course, proportional to the cube of the total change in attenuation.

This estimate is in good agreement with the computations made on actual networks. It also covers the range of greatest practical interest, since in most communication systems changes in attenuation of as much as 18 db produce undesirable variations in the levels of the different channels with respect to one another or to interfering signals. If necessary, however, it appears to be possible to go considerably farther. This possibility arises from the fact that in actual practice φ will be complex, which means that the structure acts as a variable equalizer with respect to both phase and attenuation. Ordinarily, however, only the variation of the attenuation characteristic is of interest. Since the real component of φ^3 depends upon both the real and imaginary components of φ, it is thus possible, by choosing the proper relation between these latter two quantities, to eliminate, effectively, the third order term as well as the even order terms in the general expansion. The first disturbing term is then of the fifth order, and has a very small coefficient. If we assume that the desired relation between the real and imaginary components of φ can be obtained with sufficient precision in a physical network, it appears that this process allows us to confine the distortion to 0.1 db for total variations in attenuation as great as 30 or 35 db. Since the distortion now depends upon the fifth power of the total variation in attenuation it is, of course, very small for more moderate variations. For example, under the same assumptions it is only about 0.001 db for a total variation of 12 db.

All of these relations, of course, have no utility unless structures meeting the general conditions laid down by equation (3) can be found. The simplest structure for the purpose appears to be the Π of fixed resistances shown in Fig. 3. A set of illustrative characteristics, drawn on the assumption that the parameter a equals 2, is shown at the bottom of the figure.

At first sight, this may appear to be a trivial illustration, since θ_0 and φ are merely constants, and the structure thus has only the properties of an ordinary gain control. It is possible, however, to introduce auxiliary networks by means of which θ_0 and φ can be made prescribed functions of frequency. For example, θ_0 can be altered by adding an ordinary equalizer in tandem with either terminating resistance. The modification which allows us to vary φ may be somewhat less obvious. It consists of the introduction of a symmetrical four-terminal network having the image impedance R_0, between the variable resistance and the terminals to which it was previously connected, as shown by Fig. 4.

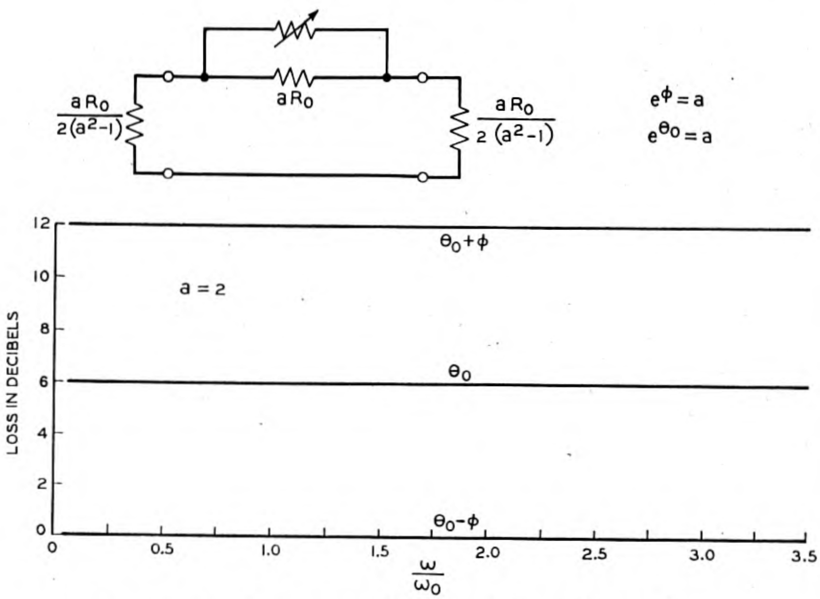


Fig. 3—The simplest type of symmetrical variable equalizer.

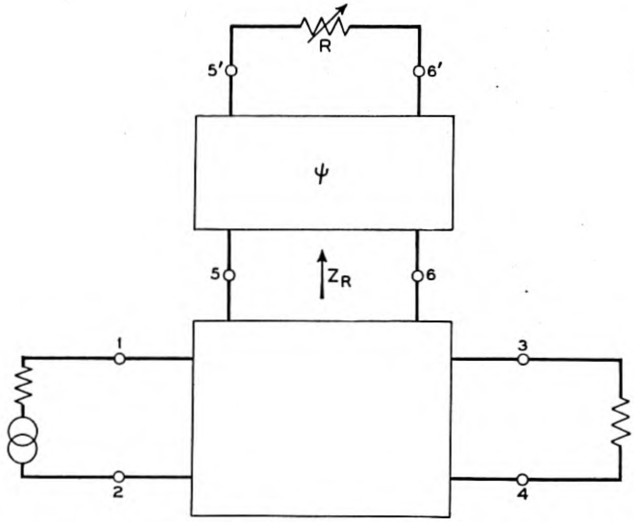


Fig. 4—Adjustment of the variable characteristic by the addition of an auxiliary network.

The effect of the added network is easily understood from the preceding equations. It will be noticed that although these equations were written under the assumption that R is a real quantity, they will still be valid if R is complex. We need therefore merely to replace R by the impedance of the auxiliary network terminated by the variable resistance. If we represent this impedance by Z_R, the appropriate expression is

$$Z_R = R_0 \frac{x + \tanh \psi}{1 + x \tanh \psi}, \tag{7}$$

where ψ is the transfer constant of the added network and x is, as before, the ratio of the variable resistance to R_0. Since reciprocal values of x still correspond to reciprocal values of $\frac{Z_R}{R_0}$, all of the preceding conditions of symmetry in the resulting family of characteristics are maintained. The simplest formulation for the new φ is secured from equation (6). Upon replacing the "x" of this expression by $\frac{Z_R}{R_0}$ we readily find that the equation becomes

$$\theta = \theta_0 + \frac{x - 1}{x + 1} e^{-2\psi} \varphi + \text{higher order terms.} \tag{8}$$

The effect of the added network is therefore merely to multiply the original φ by $e^{-2\psi}$.

An example of the use of this device in conjunction with the network of Fig. 3 is given by Fig. 5. The parameter a was chosen equal to 2, which corresponds to a maximum change in attenuation of 12 db. The auxiliary network, as will be seen, is a conventional bridged-T equalizer. The characteristics of the structure are shown by Fig. 6. The series of straight lines represents the assumed curves, while the circles show the actual computed points. The scale of the drawing is too small to show the differences between the two very clearly. The actual error, at the worst setting and frequency, amounts, however, to about 0.05 db. Of this total, about half is due to the intrinsic distortion of the structure, which in this instance is controlled by the φ^3 term, the effect of the imaginary component of φ being negligible. The remaining half is due to the failure of the bridged-T network to realize the desired ψ characteristic with sufficient precision, and could presumably be eliminated by the addition of more elements to the structure.

Since both θ_0 and ψ can be controlled by auxiliary networks, the structure of Fig. 3 is by itself theoretically sufficient to meet all requirements. There exist, however, a number of other circuits which also

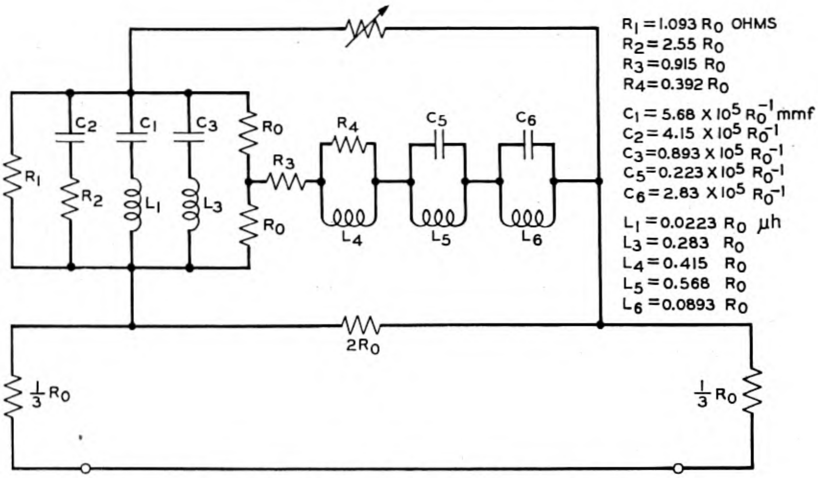


Fig. 5—An equalizer of the type shown in Fig. 3 after the addition of an auxiliary network.

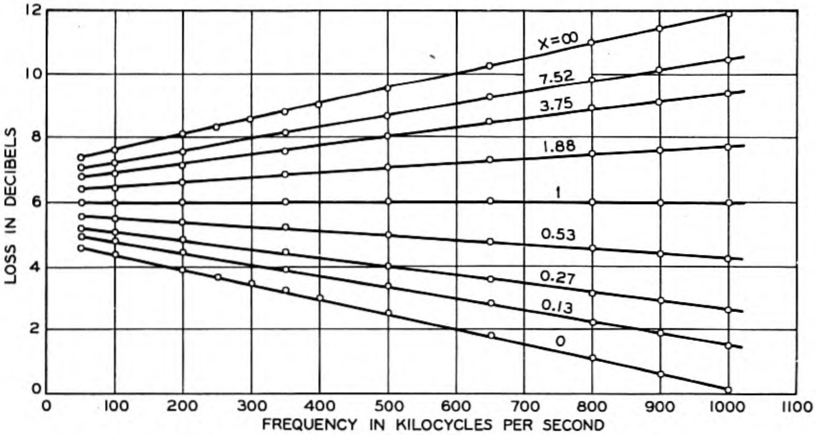


Fig. 6—Characteristics of the structure shown by Fig. 5.

satisfy the condition expressed by equation (3). For example, any structure having the general configuration of Fig. 7 will meet this condition provided the impedances Z_1, Z_2 and Z_3 are so related that when the network is considered as a 4-terminal structure transmitting from a–a' to b–b' it has a constant resistance image impedance equal to R_0 at a–a'.

In contrast to the network of Fig. 3 in which both θ_0 and φ are merely constants, most of the networks which have been found give rather complicated expressions for these two quantities. There are still a number, however, the properties of which are sufficiently simple to be of special interest. The first two are shown by Fig. 8. They have

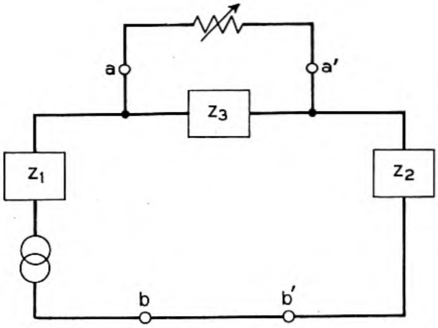


Fig. 7—Diagram to illustrate requirements on a more general form of variable equalizer.

the same design formulae, but one is terminated in a finite resistance at both ends, while an open-circuit, such as the grid of a vacuum tube, must be provided at one end of the other. Illustrative characteristics, drawn on the assumption that the impedance Z_{11} is a simple inductance are shown at the bottom of Fig. 8. It will be seen that φ is still a constant, so that an additional network must be added to control it, exactly as in the structure of Fig. 3. The reference loss θ_0, however, now varies with frequency and can be controlled by the adjustment of Z_{11}. The design impedances have been written as Z_{11} and Z_{21} in accordance with the usual convention for fixed equalizers, to emphasize the fact that the formula for θ_0 is essentially similar to the standard equalizer design formula

$$e^{\vartheta} = 1 + \frac{Z_{11}}{R}. \tag{9}$$

The choice of an appropriate Z_{11} therefore requires only routine design methods.[3] The same correspondence with the conventional formula will be found to hold also for most of the design equations to be given later.

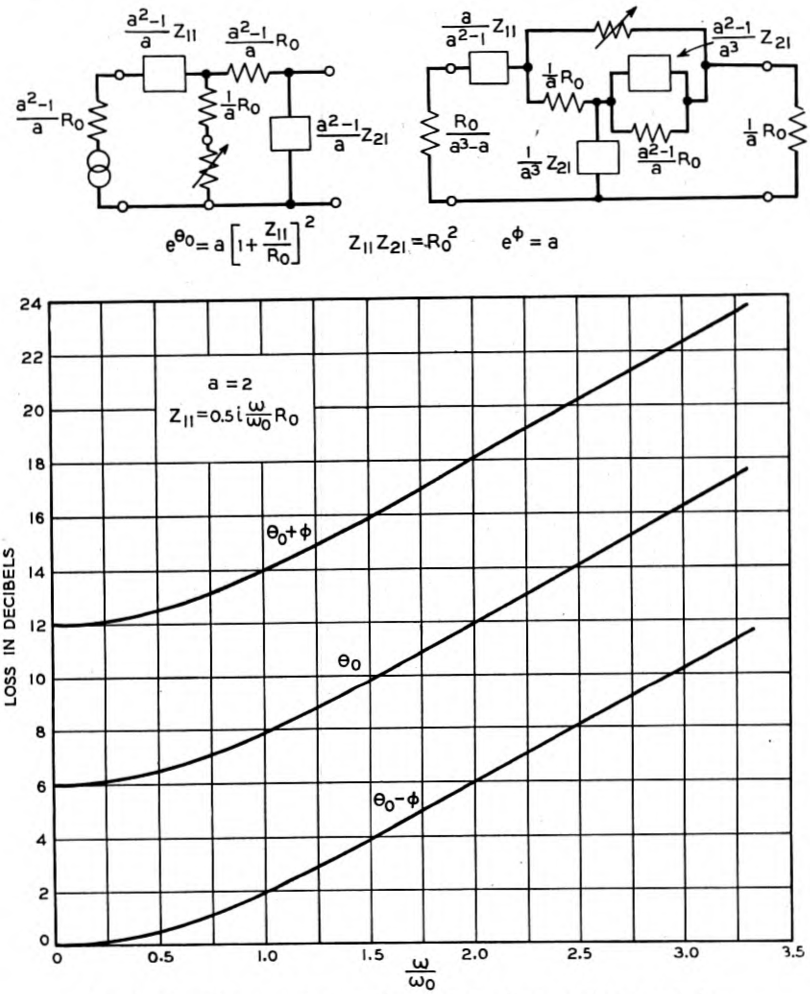


Fig. 8—Variable equalizers with varying reference characteristics.

A third simple network is shown on Fig. 9. Its properties are the converse of those secured from the structures of Fig. 8. The reference loss, θ_0, is now a constant, while φ varies with frequency in a manner

[3] See, for example, "Distortion Correction in Electrical Circuits," O. J. Zobel, *Bell Sys. Tech. Jour.*, July, 1928.

which depends upon the choice of Z. An additional control of ϕ can of course be obtained by the introduction of an auxiliary structure in front of the variable resistance. As in the previous example, the illustrative curves are drawn on the assumption that the characterizing

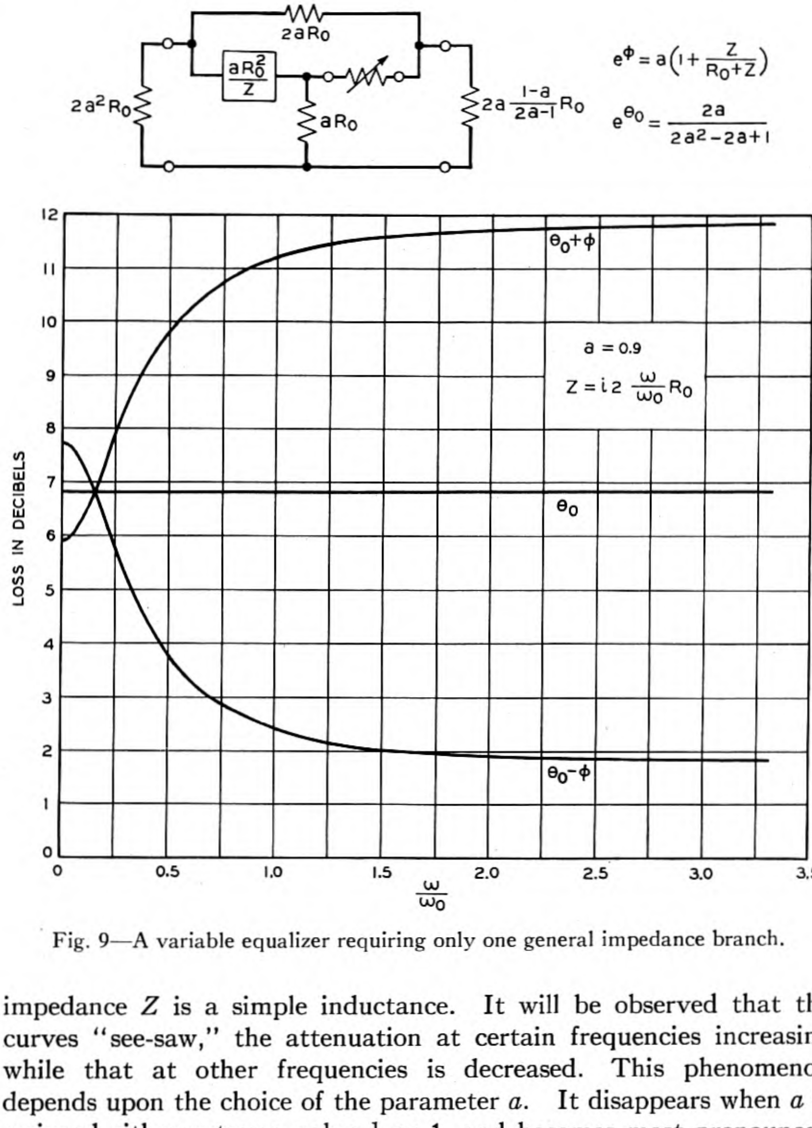


Fig. 9—A variable equalizer requiring only one general impedance branch.

impedance Z is a simple inductance. It will be observed that the curves "see-saw," the attenuation at certain frequencies increasing while that at other frequencies is decreased. This phenomenon depends upon the choice of the parameter a. It disappears when a is assigned either extreme value $\frac{1}{2}$ or 1, and becomes most pronounced at the intermediate value $a = 1/\sqrt{2}$. A similar effect can also be produced in the networks we have already considered since, as equation (8) shows, the variable attenuation will change sign if the phase shift of the auxiliary network is allowed to increase beyond 45°.

In the fourth structure, shown by Fig. 10, both θ_0 and φ are variable.

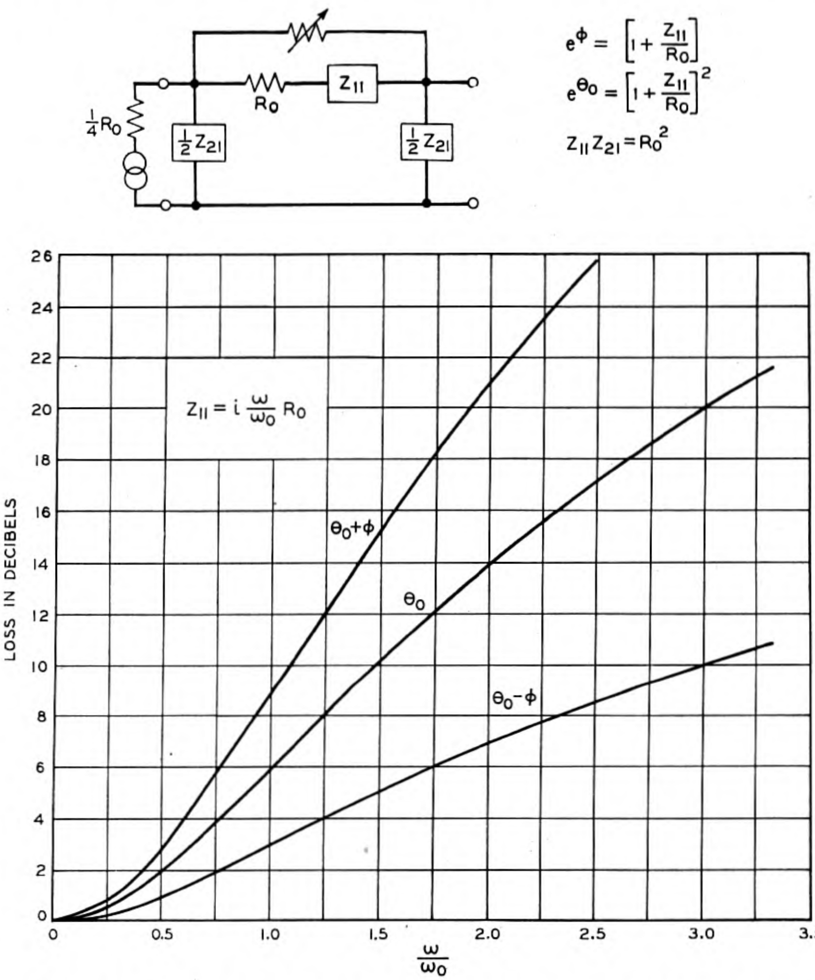


Fig. 10—A variable equalizer with a constant ratio between the reference loss and the variable characteristic.

Their ratio, however, is constant, and the overall loss characteristic of the structure is therefore proportional to some fixed characteristic at all settings of the variable resistance. This property suggests that the network may be of interest for such applications as the equalization of varying lengths of a given transmission line.

The sixth network, shown in Fig. 11, is structurally more elaborate than any which have preceded it. Its design equations are also relatively

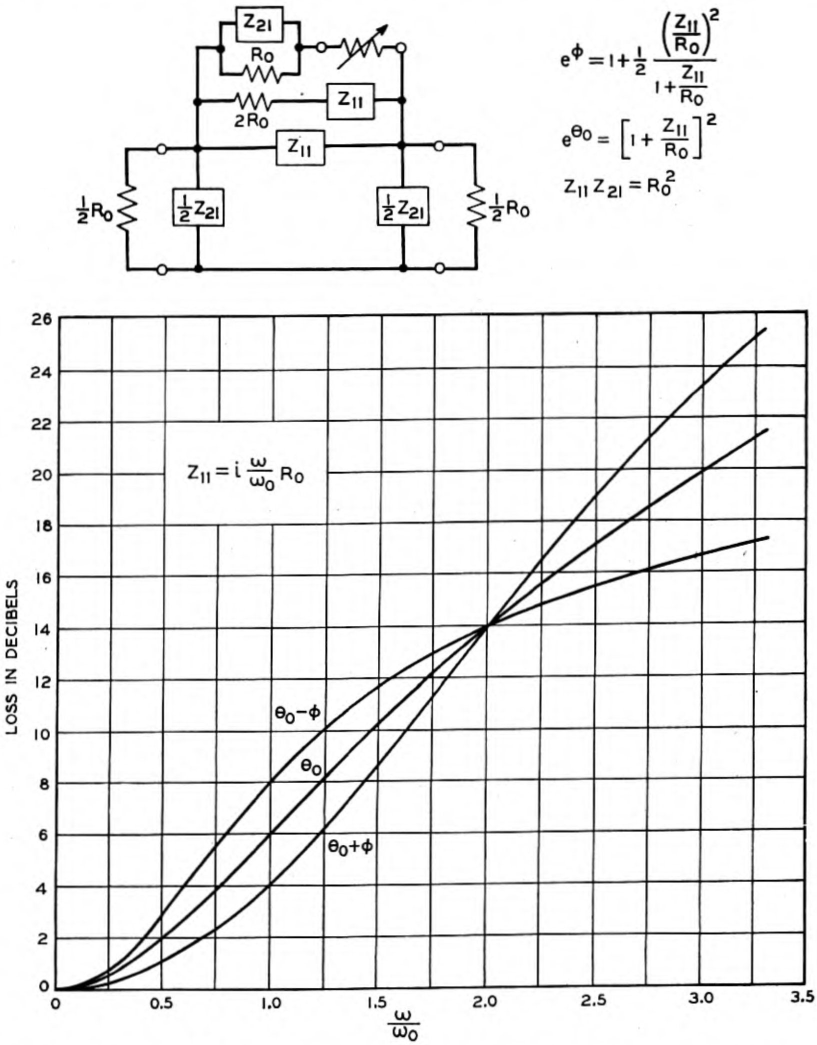


Fig. 11—A variable equalizer with zero loss at one frequency for all settings of the controlling element.

elaborate and difficult to deal with. It possesses, however, the salient property that when $Z_{11} = 0$, perfect transmission of power from one terminating impedance to the other is secured at any setting of the variable resistance. This property suggests that the network may be useful for systems where it is necessary to introduce variable equalization without attenuation of the channels having the lowest signal level.

The final structure is shown in Fig. 12. Its chief point of interest

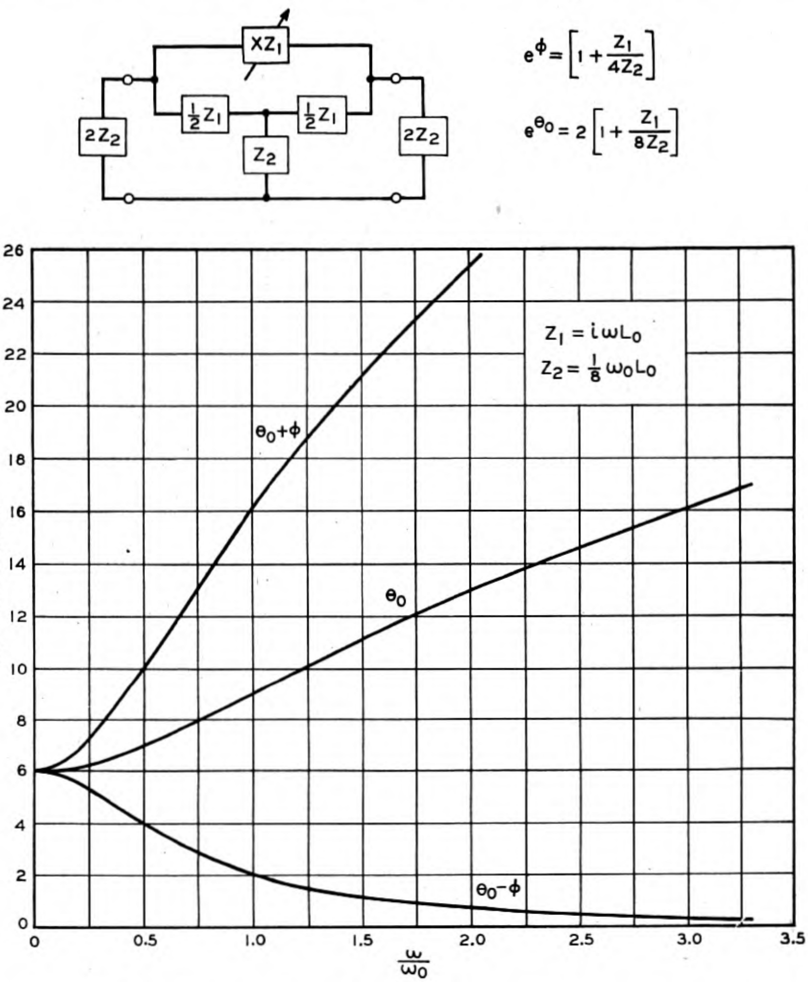


Fig. 12—A variable equalizer adapted to a general controlling impedance.

is the fact that the controlling element, instead of being a variable resistance, is a variable general impedance, which has been labelled xZ_1 in the drawing. In practical cases, of course, Z_1 will ordinarily be a simple resistance, inductance, or capacity. In addition to the variable branch the network also includes two fixed branches proportional to Z_1 and three fixed branches proportional to a second general impedance Z_2. The change from a variable resistance to a variable impedance makes little difference in the analysis. It is merely necessary to replace each R and R_0 by a Z or Z_0 in every equation. So long as equation (3), with the appropriate modification, is satisfied, as it is in this structure, the resulting family of attenuation characteristics will have the same general symmetrical form as those obtained from the resistance controlled devices. A set of curves illustrating this point is shown at the bottom of Fig. 12. They are drawn on the assumption that the Z_1 and Z_2 impedances are respectively inductances and resistances.

The structure of Fig. 12 will still function satisfactorily as a variable equalizer if it is turned inside out so that the $Z_1/2$ impedances become the terminations and the central shunt branch becomes the variable. In this event the present variable impedance must be set at its nominal value. The resulting structure is essentially the inverse of the network of Fig. 12. In the same way, of course, each of the other configurations which have been described can be replaced by its inverse.

An Explanation of the Common Battery Anti-sidetone Subscriber Set

By C. O. GIBBON

THE telephone transmitter serves to convert sound waves into their electrical facsimile; but in performing this primary function the transmitter also acts as an amplifier. Under some conditions the electrical power output of a transmitter may be more than a thousand times as great as the acoustic power activating it. Part of this greatly augmented power is dissipated in the circuit of the telephone set; part is impressed upon the telephone line, whence it is propagated on to the distant listener; and part finds its way into the receiver of the same set, where it is reconverted into sound waves. Speech or noise, picked up by the transmitter and reproduced by the receiver of the same set, is called sidetone.

Noise picked up and amplified by the transmitter and heard as sidetone tends to obscure incoming speech, thereby impairing reception. Similarly, the sound of his own voice, heard more loudly than normal as sidetone because of transmitter amplification, impels the talker involuntarily to lower his voice; thus impairing the reception of his speech at the far end of the connection. The consequent desirability of reducing sidetone has long been recognized, and operator and subscriber sets which accomplish this have been developed.

Circuit schematics of the common battery sidetone and anti-sidetone subscriber sets at present standard in the Bell System are shown in Fig. 1. The anti-sidetone set has become increasingly common during the past few years, and because of the improvements in effective transmission which it affords, bids fair ultimately to be well nigh universally employed. It is, therefore, not surprising that numerous requests have arisen for an explanation of this anti-sidetone circuit which may be more easily followed than one based on the methods usually employed in network analysis. The present paper provides an explanation by means of diagrams with a minimum of mathematical treatment which it is believed those to whom the mathematical approach does not appeal will find helpful in picturing the behavior of this circuit.

The explanation given in this paper is, however, confined to idealized conditions. No concern is given to whether the conditions necessary to exact attainment of the balances described are actually feasible;

nor is any attempt made to discuss questions of practical design beyond pointing out something of the nature of the problems involved. Equations for this anti-sidetone circuit are given and discussed in an appendix, and a vector diagram is shown which illustrates graphically relations among the currents and voltages under the ideal condition of exact balances.

Rearrangement of Circuit Patterns

Simplified explanations of anti-sidetone sets are most frequently based upon analogues with balanced arrangements resembling the

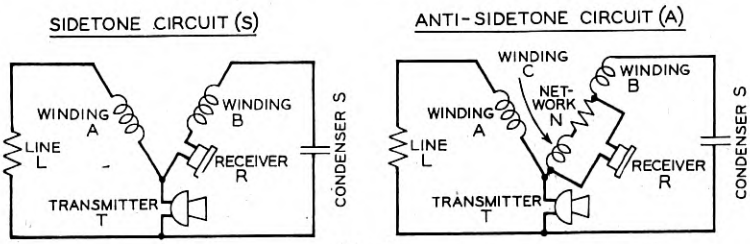


Fig. 1

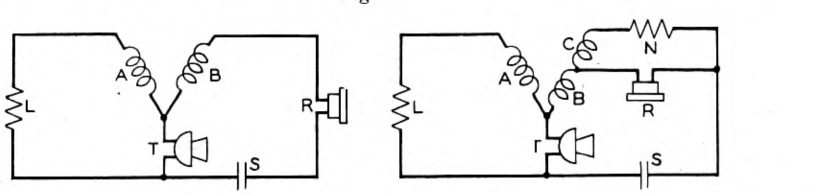


Fig. 2

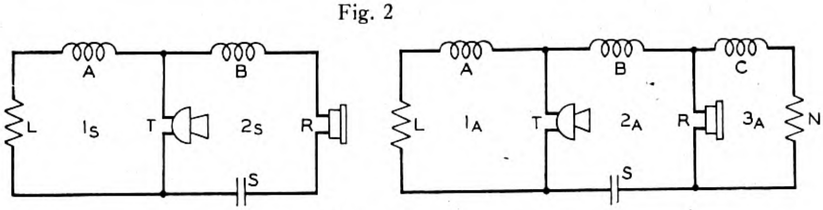


Fig. 3

Group I—Convenient schematic rearrangements

familiar circuit pattern of the Wheatstone bridge, and several such explanations have been devised for the set now to be considered. A wholly different approach will, however, be employed here. The schematics supplementing the present discussion have been arranged in groups to assist in visualizing and coordinating the steps in the explanation. The diagrams of Group I rearrange the familiar conventional schematics of the common battery sidetone and anti-sidetone circuits in Fig. 1 into the patterns most convenient for present purposes.

From the intermediate step in Fig. 2 the circuits in Fig. 3 will be seen to be the same electrically as those in Fig. 1. Inasmuch as its effects upon the features to be discussed are negligible, the ringer branch has been omitted. The circuit meshes in Fig. 3 are numbered for identification, subscripts S and A suggestively differentiating meshes of the sidetone and anti-sidetone circuits. Mesh currents and e.m.f.'s in all subsequent schematics are correspondingly identified as later described.

Complementary Sidetone Circuit

From Fig. 3 the three-mesh anti-sidetone circuit is seen to differ schematically from the two-mesh sidetone circuit only by having a balancing branch consisting of a third induction coil winding C and a network N bridged across the receiver to form the third mesh. In this theoretical discussion, N may be assumed to be a network of whatever form is capable of providing the impedance characteristics needed to meet the requirements later discussed; in practice, it becomes merely a resistance integrally comprised within the resistance component of the self-impedance of winding C. The sidetone circuit which would remain if this added branch were disconnected will be called the complementary sidetone circuit or the sidetone complement of the anti-sidetone circuit. In every reference to a sidetone circuit hereafter, the sidetone complement of the associated anti-sidetone circuit is meant.

Receiving and Transmitting Features

The theoretical features of the anti-sidetone circuit to be explained are:

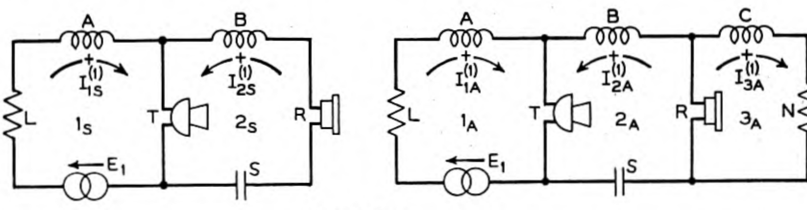
1. The receiving efficiency is the same as that of the complementary sidetone circuit.
2. The transmitting efficiency is the same as that of the complementary sidetone circuit.
3. The current through the receiver when transmitting, i.e., the sidetone, is zero.

The above efficiencies, it should be noted, are purely circuit efficiencies; they do not include electro-acoustic conversions by the instruments, and they should not be confused with questions pertaining to effective transmission performance.

Circuit Conditions When Receiving and When Transmitting

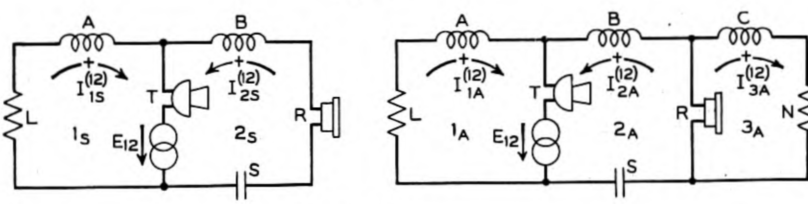
The following discussion of the diagrams in Groups II and III applies to both the sidetone and the anti-sidetone circuits.

Group II shows the e.m.f.'s impressed upon the circuits when receiving and when transmitting, and the assumed positive directions of the resulting mesh currents.[1] The schematics in Fig. 4 will be used in the later explanations of the receiving condition; but for the transmitting condition the equivalent component schematics evolved in Group III will be employed instead of Fig. 5.



Receiving

Fig. 4



Transmitting

Fig. 5

Group II—The applied E.M.F.'s and assumed * mesh currents, receiving and transmitting

By the well-known principle called Thevenin's Theorem, under the receiving condition the line and the set at its distant end may be replaced by an impedanceless generator in series with the line impedance, the e.m.f. of this generator being equal to the open-circuit voltage across the terminals of the line. Also, under receiving conditions, the transmitter will be treated as a passive impedance; and

* The curved arrows in the above and in all subsequent circuit schematics, it should be noted, do not purport to indicate the relative directions of the actual currents; but merely to denote the directions *assumed* as the positive sense of mesh currents and voltages. The selection of these directions is purely optional. As a matter of convenience, they have been so chosen that the currents through the transmitter and receiver are in every case the algebraic sum of the two contributing mesh currents.

[1] The following conventions and nomenclature are employed, see Group II:—The directions around the meshes, chosen as positive for all voltages and currents, are indicated by curved arrows. Subscripts differentiate impressed e.m.f.'s with regard to the meshes in which they are applied, and identify currents with respect to the meshes (or circuit elements—see Group IV) in which they flow. Currents are further identified with respect to the e.m.f. or e.m.f.'s to which they are due, by superscripts corresponding with the activating voltage subscripts.

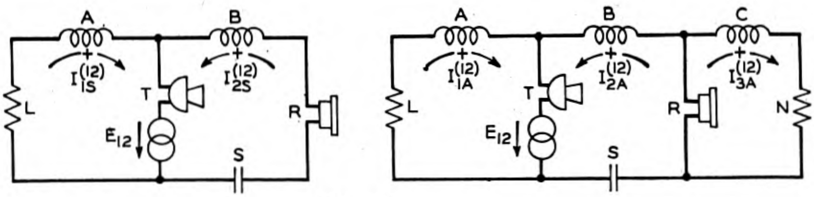


Fig. 5

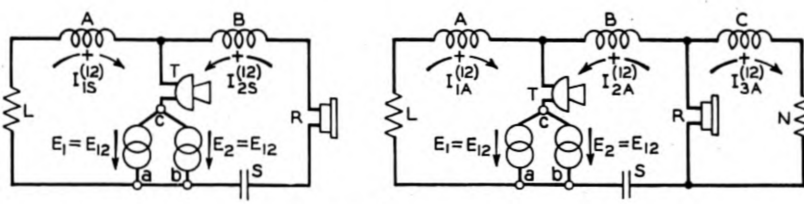
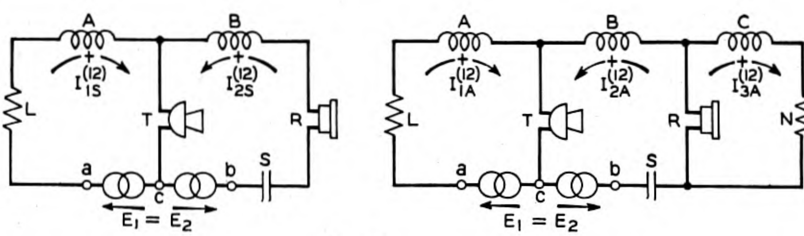


Fig. 6



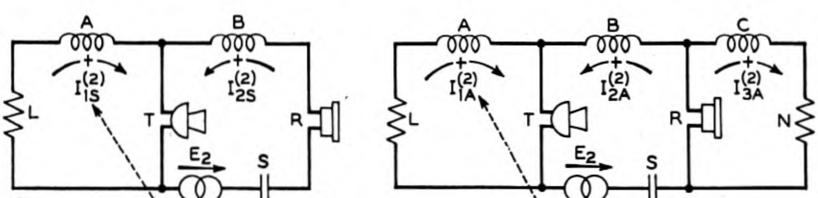


Fig. 8

$I^{(2)}_{1S} = I^{(1)}_{2S} \longleftarrow$ BY RECIPROCITY THEOREM $\longrightarrow I^{(2)}_{1A} = I^{(1)}_{2A}$

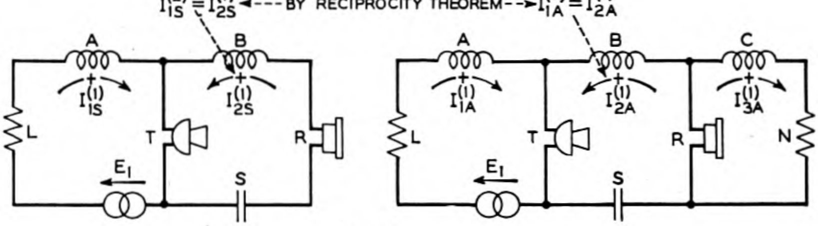


Fig. 9

Group III—Components of transmitting E.M.F.'s and assumed mesh currents when transmitting (see Fig. 5 of Group III), it will be looked upon as the same passive impedance in tandem with an impedanceless generator whose e.m.f. equals the variations in voltage drop (of the battery supply current) across the transmitter due to the changes in its impedance which occur when the transmitter is agitated by sound. This e.m.f. thus replaces in the circuit the sound engendered variations in the transmitter impedance, thereby permitting this impedance to be treated as a constant. Being impedanceless, this generator may, without effect upon the circuit, be replaced by two impedanceless generators—each having the same e.m.f. as the first—connected in parallel as shown in Fig. 6. The direct connection between points a and b, however, is shunted by the impedanceless path acb, so that the direct connection ab may, without effect, be broken as in Fig. 7. Hence, the two equal e.m.f.'s in Fig. 7, acting simultaneously, are equivalent to the single e.m.f. in Fig. 5; and the mesh currents in the two figures are, therefore, identical. Hereafter, Fig. 7, rather than Fig. 5, will be considered the transmitting condition.

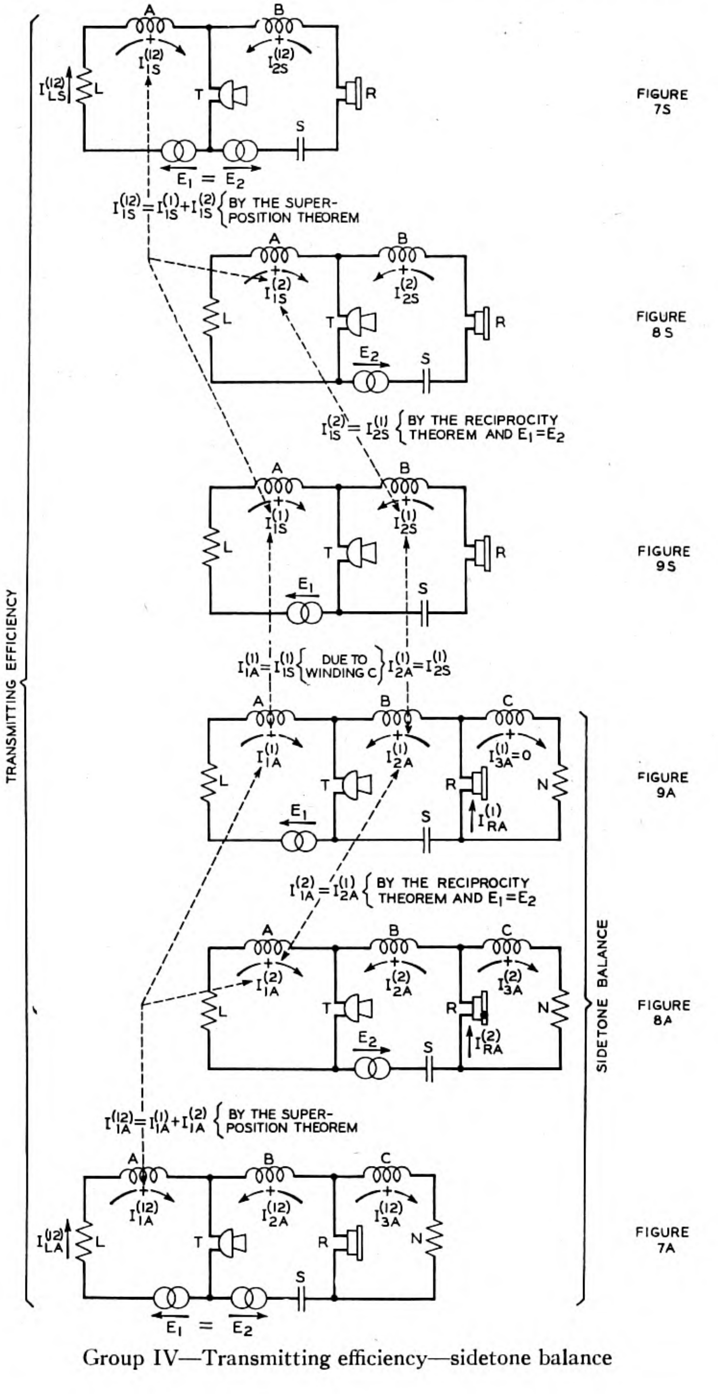
This transmitting condition may, however, be broken into two component conditions. By the fundamental principle known as the Superposition Theorem, the currents in Fig. 7 are equal to the sum of the currents which would result from each of the two e.m.f.'s acting alone. In other words, the transmitting currents in Fig. 7 are equal to the sum of the corresponding currents in Figs. 8 and 9. But by a second fundamental principle called the Reciprocity Theorem, the current at any point X in a circuit, due to an e.m.f. at any other point Y, is equal to the current which would result at Y from an equal e.m.f. at X. Applying this to Figs. 8 and 9, in which $E_1 = E_2$, the mesh currents pointed out by the arrows joining these two schematics are equal, viz.:

$$I_{1S}^{(2)} = I_{2S}^{(1)} \qquad \text{and} \qquad I_{1A}^{(2)} = I_{2A}^{(1)}. \tag{1}$$

Of the above components of the transmitting currents, those in Fig. 9 are due to an e.m.f. acting in mesh 1, i.e., in series with the line impedance. This, however, is also the condition when receiving, as will be seen by comparing Figs. 9 and 4.

Neutralizing Balance—Receiving Efficiency

Consider next the purpose of winding C. It is, of course, desirable that the transmitting and receiving efficiencies be undiminished by the anti-sidetone arrangement. If it is possible so to adjust the couplings among windings A, B and C that the current $I_{3A}^{(1)}$ in Fig. 4 or 9 is zero, the balancing branch can then be disconnected without effect



Group IV—Transmitting efficiency—sidetone balance upon the currents, and the circuit will thereby be reduced to the sidetone circuit. Hence, with this ideal adjustment of the couplings, the receiving efficiency of the anti-sidetone circuit will be the same as that of its sidetone complement.

Although equally satisfactory designs could be worked out with other polings of the coil windings, the relative inductive directions among windings A, B and C in the circuit here dealt with are such that, if a current were passed through all three in series, windings A and B would be inductively aiding; and C would be inductively opposed to both A and B. Returning to the above condition for maintaining the receiving efficiency, namely, that $I_{3A}^{(1)}$ be made zero, the windings of the coil must be so adjusted that the sum of the two voltages induced in winding C by its inductive couplings with windings A and B is equal and opposite the voltage drop across the receiver. With the windings poled as just stated, this requires that

$$(+ I_{1A}^{(1)} Z_{AC}) + (- I_{2A}^{(1)} Z_{BC}) = - (- I_{2A}^{(1)} Z_R). \tag{2}$$

This voltage balance expressed by eq. (2) will be referred to as *neutralizing balance:* its attainment requires the coil windings be adjusted to meet the relation shown by eq. (6) in the appendix.

It is important to note that neutralizing balance, and hence the efficiency relations which depend upon it, are independent of the impressed e.m.f. E_1, of the line impedance Z_L and the self-impedance of winding A, and of the network impedance Z_N and the self-impedance of winding C. This of course follows from the fact that none of these quantities is involved in eq. (2).

Transmitting Efficiency

It will now be shown that the transmitting efficiency of the anti-sidetone circuit is the same as that of its sidetone complement; and that this equality, like that of the receiving efficiencies, results from the neutralizing balance effected by winding C. This is true if, with equal transmitter e.m.f.'s in the top and bottom diagrams of Group IV, the line currents are equal, viz., if

$$I_{1A}^{(12)} = I_{1S}^{(12)}.$$

To prove this relation, refer to Fig. 7A at the bottom of Group IV and move up step by step to Fig. 9A, observing the relations between mesh currents indicated by the arrows. It will be seen that

$$I_{1A}^{(12)} = I_{1A}^{(1)} + I_{2A}^{(1)}.$$

But in Figs. 9*A* and 9*S*, due to neutralizing balance, as was shown in discussing receiving efficiencies,

$$I_{1A}^{(1)} = I_{1S}^{(1)} \qquad \text{and} \qquad I_{2A}^{(1)} = I_{2S}^{(1)}.$$

Finally, continuing from Fig. 9*S* upward to Fig. 7*S*, it is seen that

$$I_{1S}^{(1)} + I_{2S}^{(1)} = I_{1S}^{(12)}.$$

Hence,

$$I_{1A}^{(12)} = I_{1A}^{(1)} + I_{2A}^{(1)} = I_{1S}^{(1)} + I_{2S}^{(1)} = I_{1S}^{(12)}.$$

Primary Purposes of Winding *C* and of Neutralizing Balance

The above relations between the efficiencies of the anti-sidetone circuit and those of its sidetone complement are, however, merely incidental to the primary purposes of winding *C* and of the neutralizing balance which it provides. The major purpose of winding *C* is that, entirely apart from its neutralizing action, the voltages induced in it through its couplings make it possible to obtain sidetone balance by adjusting Z_N; i.e.—referring to Fig. 7*A* at the bottom of Group IV—given any value of Z_L, it is theoretically possible so to adjust Z_N that $I_{2A}^{(12)} = -I_{3A}^{(12)}$. The current through the receiver under the transmitting condition, i.e., sidetone, will then be zero. Neutralizing balance permits this adjustment of Z_N to be made without affecting the circuit efficiencies.

Sidetone Balance

The following discussion of sidetone balance will proceed on the assumption that the couplings of winding *C* with windings *A* and *B* have already been adjusted for neutralizing balance, since this condition is required to maintain the circuit efficiencies. This approach is merely a matter of convenience, however, for it will be indicated that the impedance of *N* required to effect sidetone balance is the same whether the neutralizing balance is taken into account or ignored. Although sidetone balance is made possible by the couplings of winding *C*, and the impedance of *N* needed to reduce sidetone to zero does depend upon the values to which the self and mutual impedances of this winding have been adjusted, neither the attainment of sidetone balance nor the value of Z_N required to provide it depends upon the existence of neutralizing balance.

If sidetone is to be zero, the voltage across the receiver under the transmitting condition, i.e., the sum of the voltages across *C* and *N*, must be made zero. Expressed in terms of the voltages in Fig. 7*A* at the bottom of Group IV, this requires that

$$I_{1A}^{(12)} Z_{AC} - I_{2A}^{(12)} Z_{BC} - I_{3A}^{(12)} (Z_C + Z_N) = 0. \tag{3}$$

Here, at once, the dependence of sidetone balance upon the presence of the inductively coupled third winding is apparent. Without winding C the impedances Z_{AC}, Z_{BC} and Z_C in the above expression would all be zero, the terms in which they occur would drop out, and the requirement for elimination of sidetone would reduce to $Z_N = 0$, i.e., a short circuit across the receiver.

The remainder of this discussion of sidetone balance can be carried out more conveniently in terms of the mesh currents than in terms of the above voltages. As already noted, the voltage balance just examined is equivalent to requiring that $I_{2A}^{(12)}$ and $I_{3A}^{(12)}$ in Fig. 7A be made equal and opposite. But $I_{2A}^{(12)}$ is the sum of the two components, $I_{2A}^{(1)}$ in Fig. 9A and $I_{2A}^{(2)}$ in Fig. 8A; and, because of neutralizing balance, $I_{3A}^{(12)} = I_{3A}^{(2)}$ in Fig. 8A. Furthermore, by the Reciprocity Theorem, the component $I_{2A}^{(1)}$ always equals $I_{1A}^{(2)}$; and the latter, like the former, is independent of Z_N. The condition for sidetone balance may, therefore, be expressed in terms of the currents in Fig. 8A as

$$I_{1A}^{(2)} + I_{2A}^{(2)} + I_{3A}^{(2)} = 0. \tag{4}$$

The question, then, is whether N can be so adjusted that the sum of the three mesh currents in Fig. 8A is made zero; and it is fairly evident such an adjustment for any given value of Z_L is theoretically possible. Since $I_{1A}^{(2)}$ is known to be independent of Z_N, and because inspection shows the circuit to be symmetrical with respect to L and N, it appears that $I_{3A}^{(2)}$ must be independent of L—an intuitive inference which the Reciprocity Theorem confirms. The value of $I_{2A}^{(2)}$ depends, of course, upon both Z_L and Z_N. Hence, with the value of $I_{1A}^{(2)}$ remaining fixed as Z_N is varied, and with $I_{3A}^{(2)}$ independent of Z_L but under the direct control of Z_N, it may be concluded possible to meet eq. (4) by a suitable choice of Z_N for any given value of Z_L. The value of Z_N required to attain sidetone balance is shown by eq. (7) in the appendix.

With N so adjusted that sidetone is zero, it is obvious the receiver impedance may be changed in any way whatever without upsetting the sidetone balance. The same is true of any change in the impedance of the transmitter; because this, being equivalent to a compensating change in the transmitter e.m.f., would cause all mesh currents to change in the same proportion; thus leaving the balance expressed by eq. (4) undisturbed. Hence, the impedance of N required to provide sidetone balance is independent of the receiver and of the transmitter. But as has already been seen, the couplings of winding C necessary to provide the neutralizing balance in eq. (2) do depend upon the receiver and transmitter impedances. The significance of this observation is that although the value of Z_N required to provide sidetone balance does depend upon the values of the couplings of *C*, neither the attainment of the balance in eq. (4) nor the impedance of *N* required to provide it depends upon the balance in eq. (2) being met. In other words, the neutralizing balance expressed by eq. (2), and the sidetone balance expressed by eq. (4), are mutually independent; either may be attained without the other.

Practical Considerations

With the simple types of coil and network permitted by economic and space limitations, the balances upon which the above performance of the anti-sidetone circuit depends can be obtained exactly only with a given line and at a single frequency. For practical purposes, however, exact balances are needless. Sound leakage under the receiver cap and conduction through the head structure fix a limit beyond which further reduction in sidetone is not of value. Actual designs, therefore, aim at the best compromise in reducing sidetone over the voice range and the range of line impedances important in practice, as judged by the resulting effective transmission performance obtained with the instruments employed. Under typical plant conditions, designs now in service reduce the volume of sidetone with present instruments to a level averaging around 10 to 12 db below that of the complementary sidetone sets.

APPENDIX

Algebraic Solution of Circuit Equations

Referring to Fig. 10, the following circuit equations may be written:

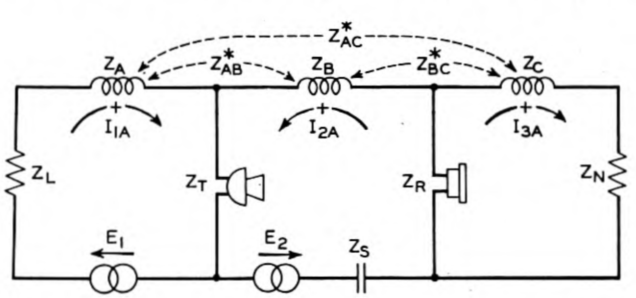
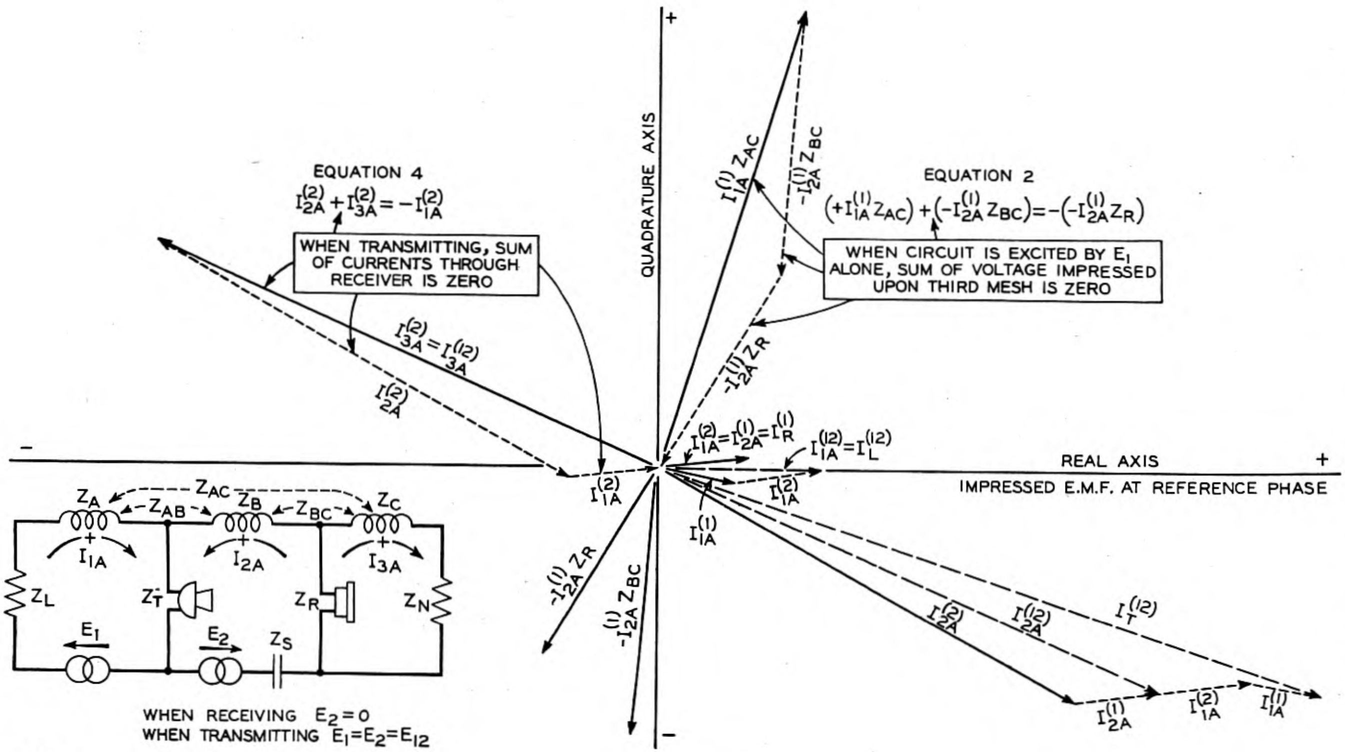


Fig. 10—* The poling of windings *A* and *B* is series aiding. Winding *C* is poled in series opposition to windings *A* and *B*.

$$\left.\begin{aligned} (Z_L+Z_A+Z_T)I_{1A}+ \quad & (Z_T-Z_{AB})I_{2A}- \quad & Z_{AC}I_{3A}=E_1 \\ (Z_T-Z_{AB})I_{1A}+ & (Z_T+Z_B+Z_R+Z_S)I_{2A}+ \quad & (Z_R+Z_{BC})I_{3A}=E_2 \\ -Z_{AC}I_{1A}+ \quad & (Z_R+Z_{BC})I_{2A}+ & (Z_R+Z_C+Z_N)I_{3A}=0 \end{aligned}\right\}. \tag{5}$$



This diagram shows the following:

1. Vectors of mesh currents due to E_1 acting alone.
2. Vectors of mesh currents due to E_2 acting alone.
3. Vector additions of the foregoing components showing the following under the transmitting condition:
   A. Vectors of the mesh currents.
   B. Vectors of the currents through the transmitter and fed into the line.
   C. The sum of the currents through the receiver is zero.
4. Vectors of voltages impressed upon the third mesh when circuit is excited by E_1 alone.
5. Vector addition of foregoing voltages showing sum to be zero.

Fig. 11—Vector diagram for assumed example of anti-sidetone common battery subscriber set circuit.

These cover both transmitting and receiving conditions: when transmitting, $E_1 = E_2$; and when receiving, $E_2 = 0$.

The relation which the induction coil must meet in order to provide neutralizing balance can be determined by solving eqs. (5) under the receiving condition $E_2 = 0$, and imposing the requirement that $I_{3A}^{(1)} = 0$. This gives as the relation to be met.

$$\frac{Z_{AC}}{Z_{BC} + Z_R} = \frac{Z_{AB} - Z_T}{Z_T + Z_B + Z_R + Z_S}. \tag{6}$$

In like manner, the value of Z_N needed to provide sidetone balance can be determined by solving eqs. (5) under the transmitting condition $E_1 = E_2$, and imposing the requirement that $I_{2A}^{(12)} + I_{3A}^{(12)} = 0$. This value of Z_N, regardless of whether or not eq. (2) is imposed as a further condition in its derivation, is found to be

$$Z_N = Z_{BC} - Z_C + \frac{Z_{AC}(Z_{AC} + Z_{BC} - Z_{AB} - Z_B - Z_S)}{Z_L + Z_A + Z_{AB}}. \tag{7}$$

Note that Z_N is here independent of Z_T and Z_R, except as these may enter implicitly as factors affecting the impedances at right in designing the coil for optimum performance with specified instruments. In other words, the transmitter and receiver may be changed without disturbing the sidetone balance. Such a change would, however, upset the neutralizing balance, thereby altering the efficiencies from those of the sidetone circuit.

Vector Diagram

Relations among the component mesh currents in an anti-sidetone circuit of this type under ideal conditions of exact neutralizing and sidetone balances, are illustrated by the vector diagram in Fig. 11. As all of the current vectors indicate current per volt impressed, those for the mesh currents under the receiving condition in Fig. 4*A* are identical with those under the component of the transmitting condition in Fig. 9*A*. Vector sums of the mesh currents show the current through the receiver and that fed into the line when transmitting, and illustrate the sidetone balance. Vectors of the three voltages acting around the third mesh in Figs. 4*A* and 9*A* are also shown, together with their summation. The latter illustrates the neutralizing balance of eq. (2).

The Occurrence and Effect of Lockout Occasioned by Two Echo Suppressors

By ARTHUR W. HORTON, Jr.

"The Time Factor in Telephone Transmission" by O. B. Blackwell (B. S. T. J. January 1932) deals with a number of problems which arise in connection with telephone circuits having long transmission times. This paper discusses one such effect, the occurrence of lockout caused by the echo suppressors involved in a long telephone connection.

The occurrence of lockout is shown to cause an increase in repetition rate, which is ordinarily small for circuits as now used commercially. The increase in repetition rate is approximately proportional to the number of lockouts occurring and to their mean duration, or to the per cent of time locked out.

The expected number of lockouts is shown to depend upon the characteristic time intervals of conversational speech, the relay hangovers, the delay of the circuit and location of the echo suppressors with respect to the ends of the circuit. Subject to certain restrictions, the expected number of lockouts increases with the delay included between the echo suppressors, and is nearly independent of the delays between the suppressors and the circuit terminals.

The mean duration of lockouts is shown to be proportional to the relay hangovers.

Introduction

When carrying on a conversation over a telephone circuit of moderate length, the subscribers are ordinarily unaware of any limitations imposed upon the free interchange of information. As the length of the circuit is increased the time factor [1] becomes increasingly important and may become manifest in a number of ways. One result of the time factor is the occurrence of echoes which become apparent when the speech energy reflected from the end of the circuit is delayed in returning to the talking subscriber. When the circuit is equipped with an echo suppressor to render this effect unnoticeable, or when a long connection of two such circuits is made, the action of the suppressors is such as to make the circuit inoperative in the opposite direction to which speech is being transmitted. Consequently the subscribers are no longer able to interchange information with the ease and rapidity that would be enjoyed on a shorter circuit.

[1] "The Time Factor in Telephone Transmission," O. B. Blackwell, *Bell System Technical Journal*, January 1932.

A circuit equipped with a single echo suppressor is always operative in one direction, and although both subscribers may start to talk at about the same instant, one or the other will always obtain control of the circuit and his speech will be heard by the other subscriber. The principal difficulties encountered on circuits of this type become apparent when the hangover times of the relays are large. There is some difficulty in interrupting since the relays do not release during the pauses between words, and a quick response following a pause by the first talker may reach the suppressing relay before it has released, resulting in a mutilation of the initial part of the response.

When two echo suppressors are used, as is the case when two circuits each equipped with an echo suppressor are connected in tandem, similar difficulties may be encountered. In addition, lockout, or blocking of transmission in both directions, may occur and may persist for an appreciable time. Since neither subscriber is aware that the other is talking, both may continue talking until one or the other of the relays releases during a pause and enables the circuit in the appropriate direction. Thus neither subscriber will be conscious of the fact that a lockout has occurred unless he realizes from the context that some part of the conversation has been lost.

This paper discusses the manner in which lockouts can occur, and presents the results of a series of tests to determine their effect upon conversation as measured by repetition rate.[2] These results indicate that the repetition rate increases with the per cent of time during which lockout occurs. It is shown that the locked out time can be approximately calculated in terms of the circuit constants and suitable characteristic intervals of conversational speech, and the calculated values can in turn be used to predict the effects of lockout on repetition rate.

In terms of the effect upon the talkers, a lockout may be considered to occur when speech currents from one talker are prevented from reaching the other talker by one of the suppressing relays and those same speech currents operate another suppressor in such a way that speech currents from the latter talker are prevented from reaching the former. This description of lockout should not be considered as a precise definition since it does not specify the duration of a lockout. No definition in terms of measurements made upon speech at the circuit terminals would be free from difficulties in practical application, such as that of determining with sufficient precision the instants at which speech is considered to start and stop, and that of determining the direction of transmission. A definition in terms of the operations of

[2] "Rating the Transmission Performance of Telephone Circuits," W. H. Martin, *Bell System Technical Journal*, January 1931.

the suppressors is somewhat simpler to formulate, but may be difficult to apply when the echo suppressors are separated geographically. In the tests to be described there was no such separation involved and consequently the operation of the suppressors could be readily observed and easily and accurately measured. Accordingly for the purpose of this paper we shall define a lockout as the condition in which the suppressors are operated in such a way that both directions of transmission are simultaneously blocked. In general, lockouts may be caused by speech, or noise, or both, but the term will be used here to apply to the case in which operations of the suppressors have been caused by speech from both ends of the circuit.

In the course of a conversation the interchange of speech is ordinarily such that the circuit is alternately disabled by the two suppressors in one direction or the other depending upon the direction of transmission. When a pause of sufficient duration occurs, the party not in control of the circuit may reply at such a time that he obtains control of the echo suppressor nearest to his end of the circuit, and a lockout can occur provided that his speech does not reach the distant suppressor until after the party formerly in control of the circuit has resumed talking and has obtained control of that suppressor. The occurrence of lockout is therefore dependent upon the time intervals in conversational speech and upon the constants of the circuit.

The Manner in Which Lockout can Occur

The characteristic time intervals of conversational speech upon which the occurrence of lockout depends, are treated in a companion paper by Mr. Norwine and Mr. Murphy.[3] It is sufficient here to define two such characteristic intervals based on a simplified concept of a conversation. Neglecting grammatical considerations we can consider speech to be composed of a sequence of vocal intervals defined and separated by silent intervals. The lengths of these silent intervals will be called resumption times. Likewise a conversation may be considered to be composed of an alternate succession of speeches, defined and separated by intervals, the lengths of which will be called response times. An ambiguity occurs when both parties talk simultaneously but, for the purpose of this discussion, it will be sufficient to allow for this situation by admitting negative response times.

Figure 1 represents a generalized four-wire circuit equipped with two echo suppressors located at different distances from the ends of the circuit. The transmission times of the different parts of the circuit are

[3] "Characteristic Time Intervals in Telephonic Conversation," A. C. Norwine and O. J. Murphy, this issue of the *Bell System Technical Journal*.

indicated on the figure with appropriate subscripts and the two directions of transmission are differentiated by the primed and unprimed notation. The suppression points are indicated by arrows which represent an opening of the transmission path when the relays, or other sup-

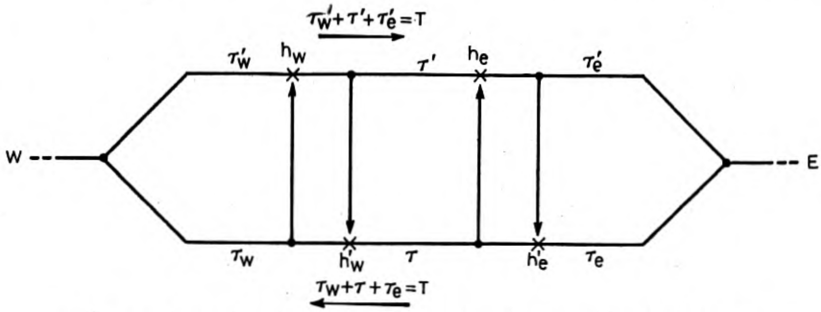


Fig. 1—Schematic of generalized four-wire circuit equipped with two echo suppressors.

pression devices are operated. The suppressing relays are specified by a notation which refers either to the particular relay or to its hangover, or releasing time. According to the definition given above a lockout exists during the time that both the relays h_e and h_w' are operated.[4]

With the exception of the beginning and end of the conversation the occurrence of lockout can be described in terms of the resumption and response times following a pause by one talker, and the constants of the circuit. Referring to Fig. 1, and considering the sequence of events following a pause by E, we shall see that two types of lockout can occur.

The first type, which is the one usually met in practice, can occur when $h_e < h_w + \tau$, and h_w releases after h_e. A response by W and a resumption by E are necessary to produce a lockout. It will persist as long as both E and W continue to talk and for an additional time equal to the delay from the end of the circuit to the first relay to release after a pause by one talker, plus the hangover time of that relay. A lockout of this type may be termed a lasting lockout.

The second type can occur when $h_w + \tau < h_e$, and h_w releases before h_e. It is possible for a response by W to arrive at h_w and operate h_w' before h_e has released thus causing a lockout wihch will be terminated when h_e releases. A lockout of this type, which may be termed a releasing lockout, can occur without a resumption by E, or if E's resumption reaches h_e' after h_e releases. If a releasing lockout has oc-

[4] Also, according to the definition, when both the relays h_w and h_e' are operated, a condition of no practical importance.

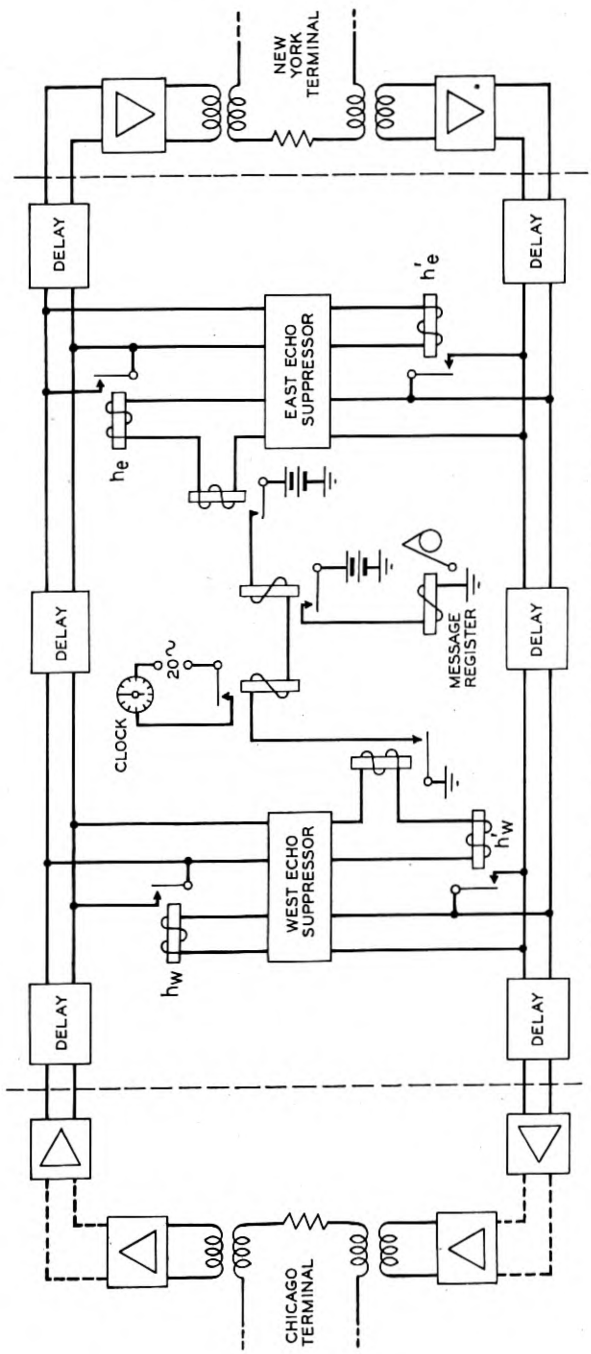


Fig. 2—Circuit arrangement used for experimental results.

curred and E's resumption operates h_e before W's response can operate h_e', a second lockout which will be of the lasting type, will at once occur. Otherwise W's response will operate h_e' giving control of the circuit to W.

Experimental Conditions and Data

To obtain experimental data of the occurrence of lockout in long distance conversations and to determine the resulting effect on repetition rate, added delay and echo suppressors were inserted at the New York end of a circuit to Chicago, Illinois. This circuit is used as a tie line by the Western Electric Company for the transaction of company business between its Hawthorne plant and New York office. The regular echo suppressor usually associated with the circuit at Pittsburgh was removed for these tests. The circuit arrangement employed is shown schematically in Fig. 2, the added equipment being included between the dotted lines. This equipment was adjusted to have zero insertion loss and the frequency characteristic was equalized to within $\pm$ 2 db from 200 to 3000 cycles. The overall net loss from toll board to toll board was 7 db. The suppressors were 44-A echo suppressors operating at a sensitivity of 31 db referred to the zero level point of the circuit, except in those cases specifically mentioned. The added delay circuits were of the acoustic type consisting essentially of a suitable length of brass pipe terminated by high quality loud speaking telephones together with the necessary amplifiers and equalizers to give zero loss over the frequency range from 200 to 3000 cycles. These delay circuits were available in units of 0.023, 0.05, 0.08, 0.10 and 0.15 second, and various combinations of these delays were used together with the tie line delay of 0.043 second to obtain the circuit conditions which were tested.

The details of the recording mechanism are indicated schematically in Fig. 2. A relay was added in series with the shorting relay of each echo suppressor, so that every operation of the echo suppressor relay was accompanied by an operation of the added relay. The simultaneous operation of these relays energized two other relays, one of which in turn operated a message register to record the number of lockouts, and the other connected a 20-cycle oscillator to a cycle counter to record the locked out time.

Service observers at New York monitored both directions of the conversation and recorded repetitions and other pertinent data regarding each call.

The circuit conditions tested are shown in Table I, the notation of which corresponds to Fig. 1. For each condition the first line refers to transmission from west to east and the second line from east to west. The hangovers are those of the relays which short the indicated transmission path, for example, the figure 0.186 in the first line of Table I refers to the hangover of the relay at the west end of the circuit which shorts the transmission path from west to east. The designation in Table I indicates the grouping of conditions for observation. All conditions having the same numeral in the designation were observed concurrently, the procedure being to observe 25 calls on condition *a*, then 25 calls on condition *b* and so on. In this way seasonal variations and uncontrolled effects at the terminals or in the transmission line have been minimized for a group of conditions bearing the same numerical desig-

TABLE I

Condition	T	τ_w	h_w	τ	h_e	τ_e
1*a*	0.139 0.139	0.043 0.043	0.186 0.200	0.073 0.073	0.146 0.146	0.023 0.023
1*b*	0.193 0.193	0.043 0.043	0.186 0.200	0.100 0.100	0.200 0.200	0.050 0.050
1*c*	0.293 0.293	0.043 0.043	0.186 0.200	0.150 0.150	0.300 0.300	0.100 0.100
2*a*	Same as 1*a*					
2*b*	0.139 0.139	0.043 0.043	0.186 0.200	0.073 0.073	0.200 0.200	0.023 0.023
2*c*	0.139 0.139	0.043 0.043	0.186 0.200	0.073 0.073	0.300 0.300	0.023 0.023
3*a*	Same as 1*c*					
3*b*	0.316 0.316	0.043 0.043	0.186	0.250 0.250	 0.146	0.023 0.023
4*a*	Same as 1*c*, suppressor sensitivities 28 db					
4*b*	Same as 1*c*, suppressor sensitivities 31 db					
4*c*	Same as 1*c*, suppressor sensitivities 34 db					
5*a*	Same as 1*c*, suppressor sensitivities 31 db					
5*b*	Same as 1*c*, suppressor sensitivities 41 db					
6*a*	Same as 1*c*, suppressor sensitivities 47 db					
7*a*	0.116 0.116	0.043 0.043	0.136 0.150	0.050 0.050	0.146 0.100	0.023 0.023
7*b*	0.116 0.116	0.043 0.043	0.136 0.170	0.050 0.050	0.210 0.146	0.023 0.023

TABLE I (*Continued*)

Condition	T	τ_w	h_w	τ	h_e	τ_e
8*a*	0.116 0.116	0.043 0.043	0.136 0.150	0.050 0.050	0.146 0.146	0.023 0.023
8*b*	0.116 0.116	0.043 0.043	0.136 0.170	0.050 0.050	0.210 0.096	0.023 0.023
9*a*	0.093 0.093	0.043 0.043	0.136 0.050	0.000 0.000	0.036 0.150	0.050 0.050
9*b*	0.093 0.093	0.043 0.043	0.136 0.150	0.000 0.000	0.136 0.150	0.050 0.050
9*c*	0.093 0.093	0.043 0.043	0.136 0.250	0.000 0.000	0.236 0.150	0.050 0.050
10*a*	0.116 0.116	0.043 0.043	0.136 0.100	0.050 0.050	0.100 0.096	0.023 0.023
10*b*	0.193 0.193	0.043 0.043	0.136 0.150	0.100 0.100	0.150 0.150	0.050 0.050
10*c*	0.293 0.293	0.043 0.043	0.136 0.150	0.150 0.150	0.250 0.250	0.100 0.100
11*a*	0.116 0.116	0.043 0.043	0.186 0.186	0.023 0.023	0.186 0.186	0.050 0.050
11*b*	0.216 0.216	0.093 0.093	0.286 0.286	0.023 0.023	0.286 0.286	0.100 0.100
11*c*	0.296 0.296	0.093 0.093	0.286 0.286	0.123 0.123	0.286 0.286	0.080 0.080

NOTES

The values of delay in the column headed τ_w include the delay of the tie line and the added artificial delay.

Circuit 3*b* arranged with relays h_e and h_w to short the echo suppressor without shorting the transmission path.

nation. Observations were also made from time to time on the tie line without added delay and with a single echo suppressor of special design. Since this condition was not subject to lockout, these observations may be used to give an indication of the seasonal effects, and to correct data obtained from the different groups of tests. These data are designated by the letter n.

The data recorded consist of the duration of each call, the number of lockouts per call, the total locked out time per call, and the number of repetitions per call. Calls having a duration less than 100 seconds are not included in the data. Table II gives the number of calls observed, the mean duration of the calls in seconds, the number of lockouts per

100 seconds ($L/100$), the per cent of time locked out, or locked out time in seconds per 100 seconds ($LT/100$), the number of repetitions per 100 seconds ($R/100$), and the number of repetitions per 100 seconds corrected for seasonal variations ($R'/100$). These rates are obtained by dividing the total number of occurrences, or locked out time by the total duration for each test condition.

TABLE II

Condition	Number of Calls	Mean Duration Seconds	$\frac{L}{100}$	$\frac{LT}{100}$	$\frac{R}{100}$	$\frac{R'}{100}$
1*a*	275	451	2.61	1.13	0.40	0.40
1*b*	275	437	2.63	1.40	0.44	0.44
1*c*	275	456	3.68	2.34	0.53	0.53
1*n*	275	401			0.36	
2*a*	200	439	2.62	1.03	0.36	0.36
2*b*	200	410	2.21	1.19	0.47	0.47
2*c*	200	393	3.86	1.54	0.45	0.45
3*a*	300	424	3.61	2.34	0.51	0.51
3*b*	300	397	5.90	1.85		
4*a*	275	457	3.26	1.63	0.53	0.51
4*b*	275	413	3.34	1.76	0.55	0.53
4*c*	275	432	3.13	2.02	0.55	0.53
4*n*	75	396			0.38	
5*a*	275	436	3.99	1.99	0.60	0.53
5*b*	275	425	4.03	2.37	0.56	0.49
5*n*	250	392			0.43	
6*a*	50	391	8.34	4.26	0.72	0.67
6*n*	125	390			0.41	
7*a*	200	410	3.00	0.79	0.52	0.41
7*b*	275	387	4.26	1.23	0.55	0.44
7*n*	75	395			0.47	
8*a*	150	387	2.51	0.74	0.49	0.36
8*b*	300	401	4.64	1.30	0.53	0.40
8*n*	100	393			0.49	
9*a*	150	413	0.83	0.02	0.43	0.36
9*b*	150	403	2.59	0.17	0.42	0.35
9*c*	150	380	5.42	1.00	0.44	0.37
9*n*	175	399			0.43	
10*a*	300	401	3.84	0.91	0.46	0.44
10*b*	300	405	4.46	1.78	0.44	0.42
10*c*	300	420	5.28	2.66	0.54	0.52
10*n*	175	439			0.38	
11*a*	300	413	1.64	0.64	0.42	0.37
11*b*	300	408	0.94	0.56	0.38	0.33
11*c*	300	430	2.99	2.28	0.56	0.51
11*n*	300	396			0.41	

Effect of Lockout on Repetition Rate

It would be reasonable to expect that the repetition rate would depend not only on the lockout rate, but also on the duration and type of lockout. Considering the data as a whole there does not appear to be any definite relation between the lockout rate and repetition rate, although in most cases an increase in lockout rate results in an increase in repetition rate. If we exclude from consideration those cases in which the lockouts are of very short duration and in which releasing lockouts occur, the data indicate a somewhat closer dependence of repetition rate on lockout rate. This suggests that the increase in repetition rate caused by lockouts may be proportional to the duration of lockouts and to their frequency of occurrence, or to the per cent of time which is locked out. Fig. 3, which shows the repetition rates,

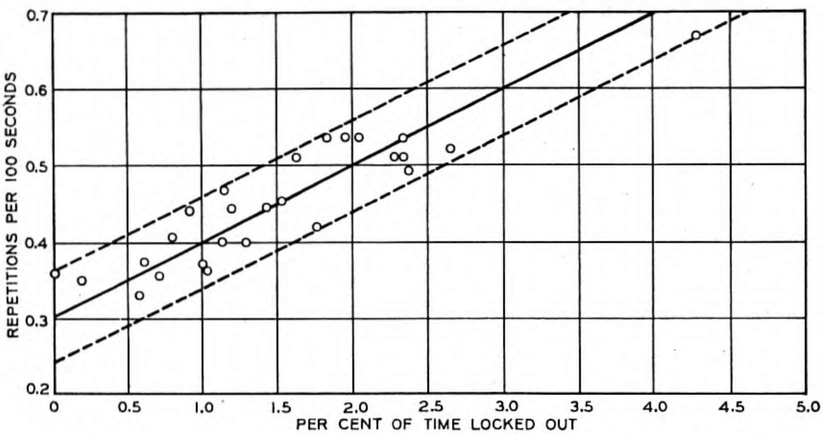


Fig. 3—Observed variation of corrected repetition rate with per cent of time locked out.

corrected for seasonal variations, plotted against the per cent of time locked out, indicates a reasonable agreement with this assumption. The correction is applied by subtracting from the observed repetition rate the difference between the observed repetition rate for the appropriate reference or n condition and a rate of 0.36, arbitrarily chosen as equal to the lowest repetition rate observed on any of the n conditions. All of the data are included in this figure. The dashed lines are drawn to include all the data and have a slope estimated as average from considering the data in individual groups. The variability in the data may in part be attributed to the variation in the distribution of lockout durations, since if two distributions have the same mean value but different spreads, the lockouts comprising the distribution which includes a greater number of long lockouts might be expected to have a greater effect upon the repetition rate. With due allowance for the variability of the data, Fig. 3 indicates that the repetition rate increases proportionally with the per cent of time locked out except possibly for values less than 0.6 per cent. The slopes of the boundary lines are such as to show about 0.1 increase in repetition rate with each 1 per cent of locked out time, and this relation appears to hold for releasing as well as lasting lockouts, and for lockouts which may be caused by relay operations by noise.

Certain qualifications are necessary in considering the significance of this result. The indicated increase in repetition rate may be partly due to other causes than lockout, as for example the effects introduced by the delay of the circuit, or by the relay hangover, during changes in the direction of speech transmission which are not accompanied by lockout. The net effect of these causes increases with circuit changes which increase the per cent of time locked out. Consequently, the latter may be taken as a criterion of the total effect, even though the contribution of the former to the repetition rate may be appreciable.

No general significance can be attached to the absolute values of the repetition rates observed in these tests since it is well known that repetition rates will differ for identical circuit conditions used with different terminal conditions and by different classes of telephone subscribers. These observed rates are significant only for comparing the relative performance of circuits under the particular conditions of use pertaining to these tests.

The significance of the results obtained depends upon the assumption that a change in lockout which causes an increase in repetition rate is an undesirable change and the transmission performance is thereby degraded. In the case of certain circuit changes which introduce changes in intelligibility the resulting changes in repetition rate can be used to determine effective transmission ratings,[5] expressed in db, of the circuits under consideration. A corresponding procedure might be applied to express the observed changes in repetition rate due to lockout in terms of db, but in the absence of data to establish the equivalence of the ratings for different types of degradation, it has not seemed advisable to do so.

Locked Out Time in Terms of Circuit Constants

Since these tests indicate that the repetition rate is proportional to the per cent of time locked out we can limit our consideration to the latter as a suitable criterion for measuring the relative merit of circuits equipped with two echo suppressors. To determine the per cent of time locked out we can measure it directly, as has been done in these tests, or it can be calculated in terms of the circuit constants by deter-

[5] "Scientific Research Applied to the Telephone Transmitter and Receiver," Edwin H. Colpitts, *Bell System Technical Journal*, July 1937.

mining the average number of lockouts per hundred seconds and the average duration of lockouts in terms of the circuit constants and obtaining the per cent of locked out time as the product of these two quantities.

The average, or expected number of lockouts per hundred seconds can be approximately determined from the circuit constants and the distributions of response and resumption times. It is shown in the appendix that, subject to certain assumptions, the probability of lockout following a pause is given by

$$P = \int\int p_1(x)\, p_2(y)\, dx\, dy, \tag{1}$$

in which $p_1(x)\, dx$ and $p_2(y)\, dy$ are the probabilities that, following a pause, the resumption time will be between x and $x + dx$ and the re-

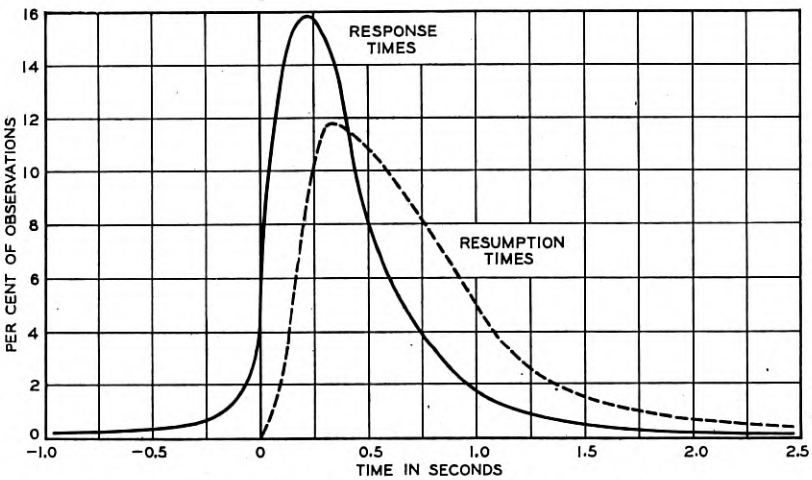


Fig. 4—Observed distribution of resumption and response times.

sponse time will be between y and $y + dy$. As suitable approximations to these probabilities we may take the observed distributions of resumption and response times. Mr. Norwine and Mr. Murphy, in their accompanying paper,[3] give distributions of resumption and response times which are shown in Fig. 4. These distributions are expressed in terms of the total number of resumptions, or responses and consequently the data are an approximation to the conditional probability that if a resumption or response has occurred, the resumption or response time will be between t and $t + dt$. The use of these data will

[3] Loc. cit.

therefore result in calculated values of the probability of lockout which are proportional to the desired probability, and if the value of the integral calculated from their data is p, then

$$P = kp, \tag{2}$$

where k is a constant of proportionality which depends on the average number of pauses occurring, and which can be determined by comparing observed and calculated results.

The observed lockouts per hundred seconds plotted against the calculated probability of lockout for each circuit condition are shown in Fig. 5 for lasting lockouts and in Fig. 6 for releasing lockouts. The

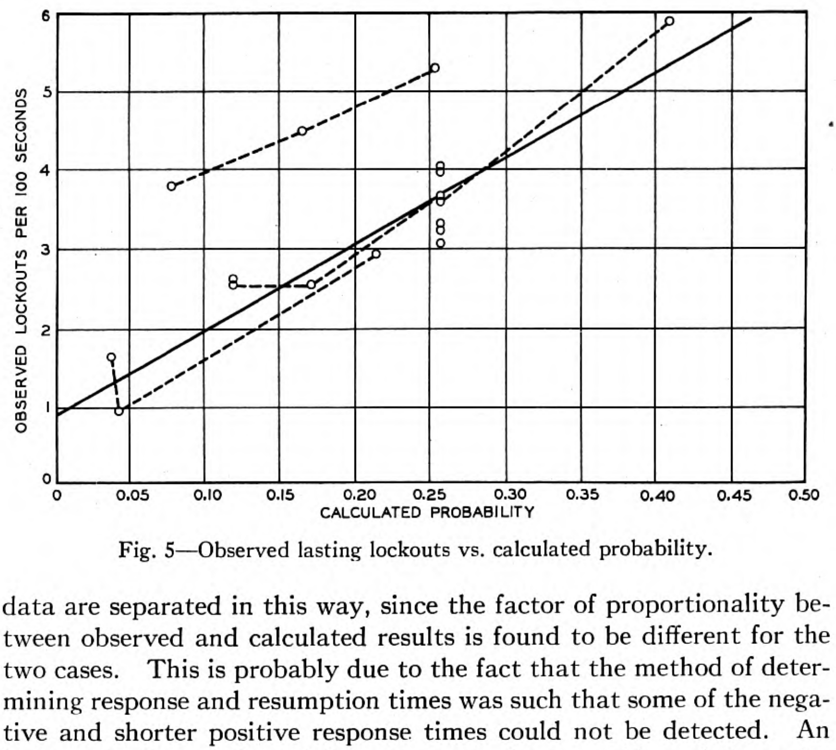


Fig. 5—Observed lasting lockouts vs. calculated probability.

data are separated in this way, since the factor of proportionality between observed and calculated results is found to be different for the two cases. This is probably due to the fact that the method of determining response and resumption times was such that some of the negative and shorter positive response times could not be detected. An increase in the number of these response times would result in an increased probability of releasing lockouts, which would tend to bring the two sets of data into agreement. Greater accuracy might be obtained if the distribution of response times were to be more accurately determined, but the present data are sufficient for approximate calculations.

In both figures the data obtained in a single group of tests are connected by dotted lines. The solid lines are the best estimates to represent the two complete sets of data. In the case of Fig. 5 the solid line was determined by the method of least squares, omitting the data of group 10. This omission appears to be justified since these data are consistent among themselves and yield a factor of proportionality

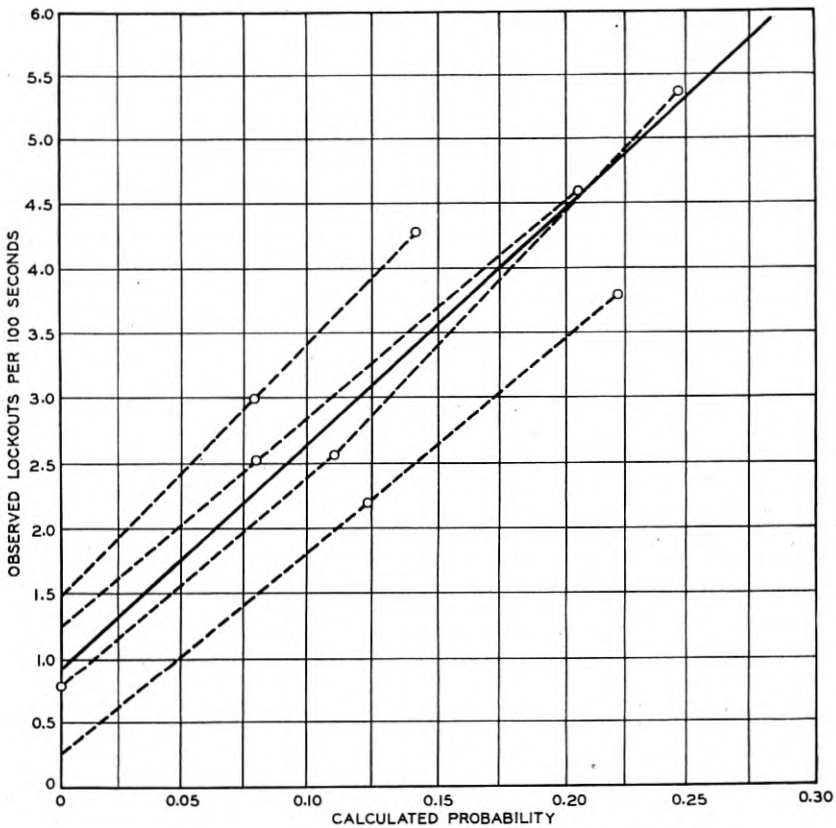


Fig. 6—Observed releasing lockouts vs. calculated probability.

which is consistent with the rest of the data, and since it is known that many uncontrolled factors may influence the results of one particular group of tests. In the case of Fig. 6 the solid line was obtained by averaging the slopes and constant terms of the individual dotted lines.

Both sets of data indicate that about 0.9 lockout per hundred seconds occurs when the calculated probability of occurrence is zero. This is undoubtedly due to non-synchronous action of the suppressors, caused by slight variations in sensitivity, changes in effective hangover caused by changes in sensitivity and by occasional relay chatter. This conclusion is confirmed by the tests made with no delay between the suppressors, in which lockout is obviously impossible with synchronous action, but in which lockouts were actually obtained in amount consistent with the rest of the data.

Figures 5 and 6 show that the number of lasting and releasing lockouts can be calculated from the circuit constants and the distributions of response and resumption times. Approximations which are suffi-

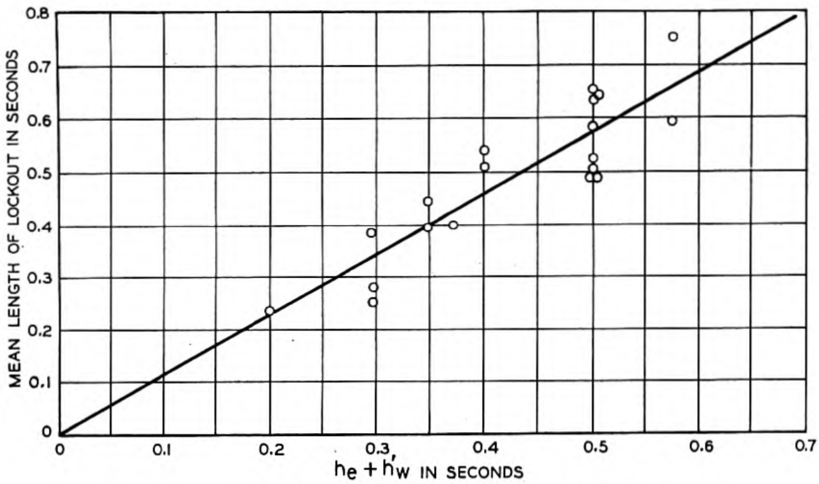


Fig. 7—Observed length of lockout as a function of relay hangovers.

cient for practical purposes for calculating the number of lasting and releasing lockouts are respectively

$$L_l = 0.9 + 11.0\,p, \tag{3}$$
$$L_r = 0.9 + 17.7\,p. \tag{4}$$

The duration of a lockout is obviously dependent upon the way in which the subscribers talk and upon the hangovers of relays h_w and h_e'. Lockouts of several seconds duration have frequently been observed but most frequently the duration of lockouts appears to be short and determined primarily by the relay hangovers. Figure 7 shows the mean duration of lasting lockouts plotted as a function of the sum of the relay hangovers, $h_e + h_w'$. The straight line is the least square representation of the data, which is

$$D_l = 0.002 + 1.16\,(h_e + h_w'). \tag{5}$$

The constant term in this equation can be neglected for approximate calculations.

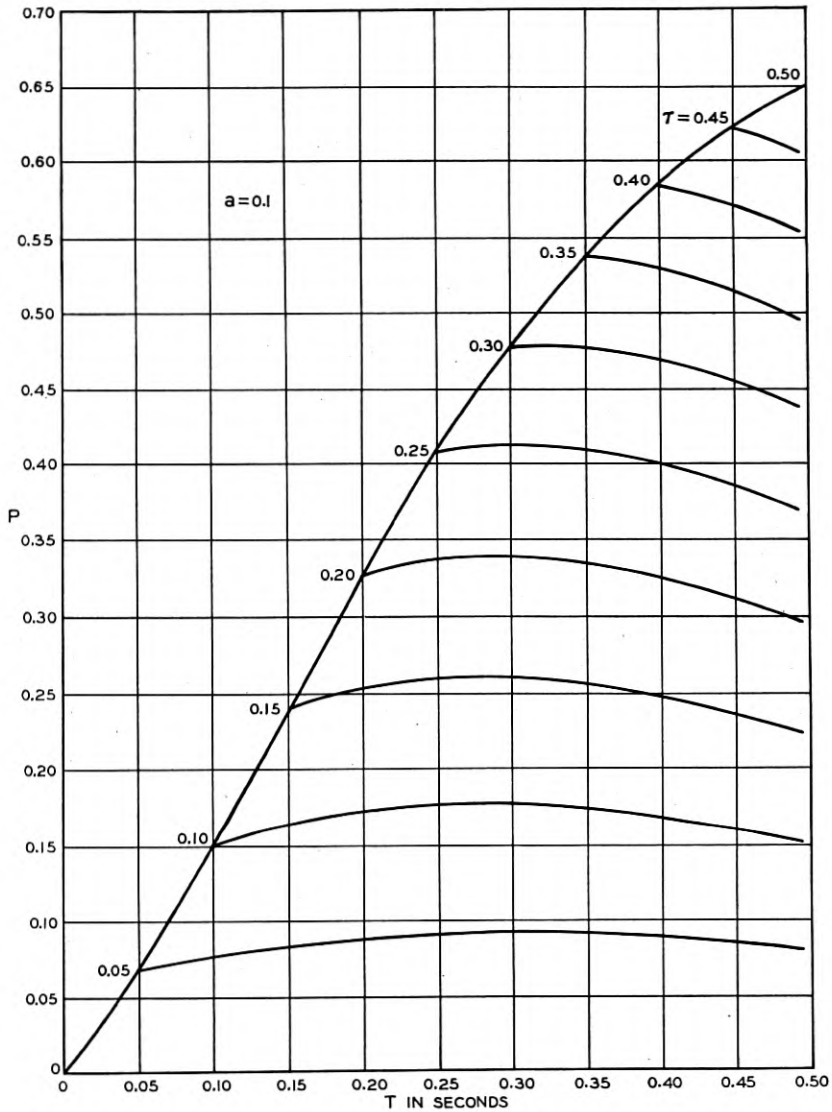


Fig. 8—Calculated probability of lockout as a function of total circuit delay.

Since the duration of lasting and releasing lockouts is not the same, releasing lockouts being of short duration, and since the two were not separately observed, the data are insufficient to determine the duration of releasing lockouts directly. However, tentative calculations indicate that approximate results can be obtained by assuming that the mean duration of releasing lockouts is about one-quarter that of lasting lockouts or

$$D_r = 0.29\ (h_e + h_w'). \tag{6}$$

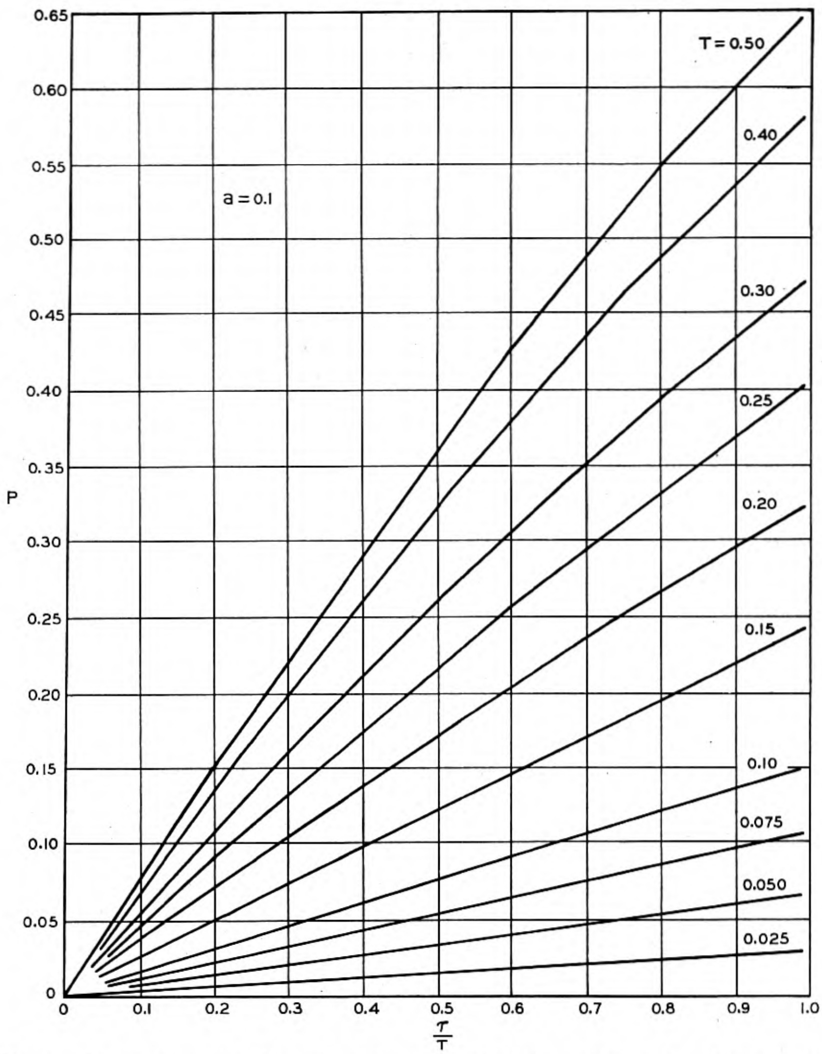


Fig. 9—Calculated probability of lockout as a function of the ratio of the delay between the suppressors to the total circuit delay.

With the above relations between probability of lockout and circuit constants, number of lockouts and probability of lockout, and mean duration of lockouts and relay hangovers, it is possible to determine the per cent of time locked out from the circuit constants. Since this is proportional to the repetition rate, a measure of relative circuit performance is obtained in terms of the circuit constants.

As an example of such calculations let us assume that $\tau_w = \tau_w' = \tau_e = \tau_e'$, $\tau = \tau'$ and $T = T'$, and $h_w = h_e' = 2\tau_w + a$. Then the constants of integration determined in the appendix become,

$$a = a,$$
$$b = a + T - \tau,$$
$$c = a + T + \tau,$$

and the probability of a lasting lockout is proportional to

$$P = \int_{-\infty}^{a} p_2(y)dy \int_{a+T-\tau}^{a+T+\tau} p_1(x)dx + \int_{a}^{\infty} p_2(y)dy \int_{y+T-\tau}^{y+T+\tau} p_1(x)dx. \quad (7)$$

Values of this probability for $a = 0.1$ are shown in Fig. 8 as a function of the transmission time T with τ, the delay between the suppressors as a parameter and in Fig. 9 as a function τ/T with T as a parameter. The curves are not extended beyond $T = 0.5$ since smaller values are thought to cover the range of practical interest. Furthermore, for large values of T there is some evidence that the effect of the transmission time would be noticed by the subscribers with a consequent change in the distributions of resumption and response times.

These curves indicate that for a constant value of τ, the delay between the echo suppressors, there is little change in the probability of lockout as the total delay of the circuit T is increased, and for a constant value of T the probability of lockout is approximately proportional to τ.

To continue with a more specific example, let us consider a telephone connection consisting of two four-wire circuits each equipped with an echo suppressor in the center of the circuit as shown in Fig. 10. In the notation of Fig. 10 the relay hangovers are each equal to $\tau + 0.100$ and the constants of integration are

$$a = 0.100,$$
$$b = 0.100 + \tau,$$
$$c = 0.100 + 3\tau.$$

Since the two circuits are assumed equal, only lasting lockouts are theoretically possible and the curves of Fig. 8 may then be used to determine p in terms of τ as defined by equation (7), which in turn may be used to determine the expected number of lockouts from equation (3). The mean duration of lockout is obtained by inserting the value of the relay hangover in equation (5) giving

$$D = 0.234 + 2.32\,\tau.$$

The product of D with the expected number of lockouts per hundred seconds is then equal to the per cent of time locked out, which is shown in Fig. 10 as a function of τ. By using the relation shown in Fig. 3 a

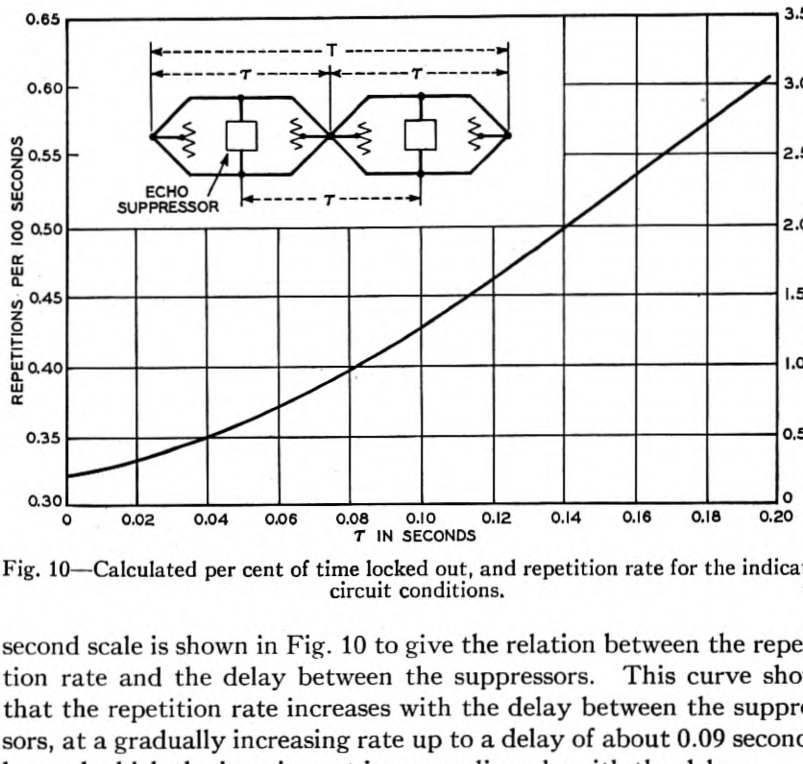


Fig. 10—Calculated per cent of time locked out, and repetition rate for the indicated circuit conditions.

second scale is shown in Fig. 10 to give the relation between the repetition rate and the delay between the suppressors. This curve shows that the repetition rate increases with the delay between the suppressors, at a gradually increasing rate up to a delay of about 0.09 seconds, beyond which the impairment increases linearly with the delay.

Summary

It has been shown that two types of lockout, lasting and releasing lockouts, may occur in telephone connections involving two echo suppressors, and the manner of their occurrence has been discussed.

The results of an experimental investigation show that the occurrence of lockouts causes an increase in repetition rate, which is approximately proportional to the per cent of time locked out.

There has been presented a theoretical method for calculating the expected number of lockouts in terms of the circuit constants which depends upon the characteristic time intervals in conversational speech. The values which have been calculated with experimentally determined constants are shown to agree with the observed values.

The average duration of lockouts has been found to be proportional to the hangovers of the relays effective in lockout.

Since the per cent of time locked out is equal to the product of the average number of lockouts per hundred seconds and the average duration of lockouts, it may be determined in terms of the circuit constants, and used as one of the criteria of the relative performance of the circuits under consideration.

Specific examples of such calculations have been used to illustrate the relations between the expected number of lockouts and the circuit constants, and between the repetition rate and the constants of a particular circuit configuration.

Subject to certain restrictions on the relations between the circuit constants, it appears that the number of lockouts and the resulting increase in repetition rate are approximately proportional to the delay included between the echo suppressors.

In conclusion I wish to express my appreciation to my associates who have contributed to this study; in particular to Dr. G. R. Stibitz who first developed the theoretical approach to the problem, to Mr. W. R. Bennett and Mr. B. D. Holbrook who have contributed to the extension of this approach, and to Mr. A. C. Norwine and Mr. O. J. Murphy who obtained the distribution functions used in the calculations and conducted the experimental work.

Appendix

To assist in formulating an expression for the probability of lockout a number of simplifying assumptions have been made, as follows:

> Pauses in speech are sufficiently separated to be considered as independent events, or in other words the sequence of events occurring at one pause have no effect upon those occurring at another.
>
> Following a pause each speaker can start speaking only once and only one of three events can occur.
>
> 1. The original speaker regains control of the circuit.
> 2. The other speaker obtains control of the circuit.
> 3. Lockout occurs.
>
> Resumption and response times are independent.
>
> The distributions of response and resumption times are independent of the delay of the circuit and the disposition of the echo suppressor.
>
> The operate times of the suppressors are sufficiently small to be neglected.

Let $p_1(t)dt$ be the probability that the speaker in control of the circuit will resume speaking in the interval t to $t + dt$ after pausing and let $p_2(t)dt$ be the probability that the speaker not in control of the circuit will start speaking in the interval t to $t + dt$ after hearing the other speaker pause. In the latter case t may be negative. Then the probability that, following a pause, a resumption will occur in the interval x to $x + dx$ and a response will occur in the interval y to $y + dy$ is given by

$$p_1(x)\, p_2(y)\, dx\, dy,$$

and the probability of lockout following a pause is given by

$$P = \int\int p_1(x)\, p_2(y)\, dx\, dy,$$

in which the integration is to be performed over the region in the xy plane which contains those values of x and y for which lockout occurs.

Assuming that either subscriber is equally likely to have control of the circuit at any instant, the probability of a lockout following a pause by either party is given by the average of the probabilities for the two parties.

In determining the limits of integration there are three cases to be considered. Assuming a pause by E

$$\begin{aligned} &\text{I.}\ h_e < h_w + \tau, \\ &\text{II.}\ h_w + \tau < h_e < h_w + \tau + \tau', \\ &\text{III.}\ h_w + \tau + \tau' < h_e. \end{aligned}$$

In case I only lasting lockouts can occur while in cases II and III both lasting and releasing lockouts can occur. Case I will be used to illustrate a method of determining the limits of integration which can also be applied to cases II and III for which the results will be stated without proof.

In Fig. 11 which is based on the circuit of Fig. 1, time is represented horizontally and distances vertically, upward from the central line, which represents the east end of the circuit, for transmission from W to E and downward for transmission from E to W. Consider a pause by E occurring at $x = 0$ at A. The line $ABDG$ represents the transmission of this pause to W. The point H obtained by projecting G to the top line determines the point $y = 0$. The points C and F represent the instants at which h_e and h_w release. If E resumes in the interval AI, the resumption will arrive at the input of h_w before h_w has released as determined by the point F, and E retains control of the circuit. If, on the other hand W responds at any time prior to

J the response will be blocked by h_w until the time represented by K and it will then be transmitted to the end of the circuit as shown by the line $JKLM$. If now E resumes at any time after P the resumption

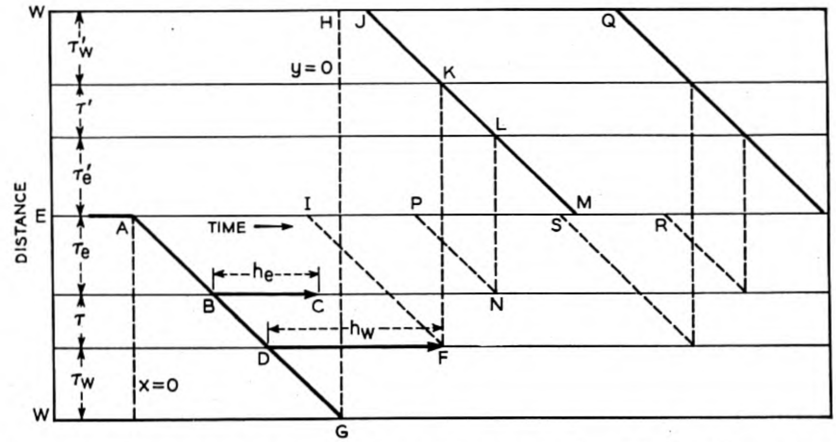


Fig. 11—Time relations in four-wire circuit for determination of limits of integration.

will be blocked by h_e' since W will have obtained control of the circuit. A resumption in the interval IP will result in lockout since W will control h_w' and E will control h_e. If W responds at some time after J, say at Q, a similar argument can be used to show that E must resume in the interval SR to cause lockout. If we let

$$HJ = a,$$
$$AI = b,$$
$$AP = c,$$

it can be shown that

$$AS = y - a + b,$$
$$AR = y - a + c,$$

and therefore the region of integration is defined by

$$b < x < c, \qquad -\infty < y < a,$$
$$y - a + b < x < y - a + c, \qquad a < y < \infty,$$

in which a is the time interval the speaker not in control must wait after hearing the other speaker pause in order to enable the response to get through the circuit; b is the time interval after the speaker in control pauses, during which he can gain control by resuming, regardless of what the other speaker does; c is the time interval the speaker in control must pause in order to make it possible for the other speaker to get a response through the circuit.

These constants have the values

$$
\begin{aligned}
a &= h_w - (\tau_w + \tau_w'), \\
b &= h_w, \\
c &= h_w + (\tau + \tau').
\end{aligned}
$$

Case II. By the same method the regions of integration are determined to be, for lasting lockouts

$$
\begin{aligned}
&y < a, \qquad b < x < c, \\
&y < a, \qquad y - a + b < x < y - a + c,
\end{aligned}
$$

for releasing lockouts, blocked by h_w,

$$y < a, \qquad \beta < x < \infty,$$

for releasing lockouts without blocking,

$$a < y < \alpha, \qquad \beta < x < \infty,$$

in which α and β are defined by

$$
\begin{aligned}
\alpha &= h_e - \tau - (\tau_w + \tau_w'), \\
\beta &= h_e.
\end{aligned}
$$

Case III. As before we obtain the regions, for lasting lockouts

$$
\begin{aligned}
&y < a, && b < x < \beta, \\
&a < y < \gamma, && y - a + b < x < \beta, \\
&\gamma < y < \infty, && y - a + b < x < y - a + c,
\end{aligned}
$$

for releasing lockouts blocked by h_w and h_e,

$$y < a, \qquad \beta < x < \infty,$$

for releasing lockouts blocked by h_e,

$$a < y < \gamma, \qquad \beta < x < \infty,$$

for releasing lockouts without blocking,

$$\gamma < y < \alpha, \qquad \beta < x < \infty,$$

in which α and β have the values given above and

$$\gamma = h_e - (\tau + \tau') - (\tau + \tau_w').$$

Characteristic Time Intervals in Telephonic Conversation

By A. C. NORWINE and O. J. MURPHY

Two-way conversation is arbitrarily defined in terms of vocal intervals and the pauses between them. These quantities, as determined by the presence or absence of speech energy, have been measured from continuous oscillograms of calls on a New York-Chicago telephone circuit used for Bell System business, and the results of statistical analyses of these data are presented.

Introduction

THE time pattern of a conversation may be described in terms of the periods during which speech energy is issuing from the lips of each talker, the pauses with which each intersperses his speech, and the periods after the termination of a talker's speech during which the listener prepares to reply. On a telephone circuit this can be determined by the presence or absence of speech energy within the circuit, measured by an appropriate recording instrument. It is with observations of this type and the measurement of time intervals in conversation obtained in this manner with which the present paper is concerned.

It will be well to keep in mind that the fundamental basis of these measurements is the presence or absence of speech energy. Many of the pauses recorded in this study are of the type which are known to occur within sentences, phrases, or even within words. Some of these are insufficient in duration to interrupt the continuity of the flow of speech, and some are too short to be noticed by a listener. The intervals as defined in this paper probably do not, therefore, exactly correspond to those which would be observed by a person listening to the conversations.

The study and measurement of these intervals were originally undertaken to furnish information needed in the application of probability theory to the occurrence of lockouts on toll telephone circuits equipped with tandem voice-operated devices. This problem is treated in a companion paper by Mr. A. W. Horton, Jr.* Since that time, however, parts of the data have been used in various other technical applications, and it is therefore thought that the results of the study may have some general interest.

* "The Occurrence and Effect of Lockout in Telephone Connections Involving Two Echo Suppressors," Arthur W. Horton, Jr., this issue of the *Bell System Technical Journal.*

Nature of the Problem

In the simplest case of conversational interchange each party speaks for a short time, pauses, and the other party replies. The time intervals are then simply the lengths of time each party speaks and the lengths of the pauses between speeches. The period during which there is speech may be called a talk-spurt, and the length of the pause may be called the response-time. These two quantities would then suffice to describe this simple type of interchange.

In many instances, however, the process is not so orderly; for example one speaker may pause and then resume speaking, or the listener may begin to reply without waiting for the end of the talker's speech. The possible, and indeed frequently encountered, variations of the simple cycle of which the preceding examples constitute only a fraction make it necessary to carefully define and delimit the elements into which a conversation may be resolved. It is believed that any telephonic conversation between two persons can be completely described in terms of the presence or absence of energy by the following time elements:

> A *talkspurt* is speech by one party, including his pauses, which is preceded and followed, with or without intervening pauses, by speech from the other party perceptible to the one producing the talkspurt. Obvious exceptions to this definition are the initial and final talkspurts in a conversation. There may be simultaneous talkspurts by the two talkers; if one party is speaking and at the same time hears speech from the other *double talking* is said to occur.
>
> *Resumption time* is the length of the pause intervening between two periods of speech within a talkspurt.
>
> *Response time* is the length of the interval between the beginning of a pause as heard by the listener and the beginning of his reply. It may be positive or negative. The pause to which reference is made ordinarily occurs at the end of a talkspurt but may be a pause followed by a resumption of speech by the first talker.

In the terms of these definitions a telephone subscriber "hears" or "perceives" when voice currents flow in his receiver; a possible lack of attention or other failure to appreciate what is "heard" is not considered. Likewise, it should be stressed that pauses are not confined to the intervals between words or sentences but may occur within words; in the measurements described herein they are determined solely by the absence of voice energy on the circuit.

In addition to these natural conversational elements there is a fourth item which is sometimes imposed by the configuration of toll circuits, namely *lockout*.[1] Lockouts did occur on the circuit carrying the conversations which provided the data for this study, due to the special circuit arrangement employed at the time, but their occurrence will not be treated in this paper.

The specific information desired was the probability that a conversational element would have any given duration t. The true probability in each case can be approximated, except for a scale factor, by a distribution curve of experimental data depicting the fractions of the total number of observations of the quantity which lie within each of a regular progression of time cells of a chosen width. It is in this form that the data will be presented.

Data Source

Some preliminary data were obtained from observations on local inter-office calls between various members of the staff of Bell Telephone Laboratories. Members of the non-technical groups were included among the talkers, some of whom were women. Equipment added to the telephone circuit for the purpose of recording was held at a minimum and its presence and action were not noticed by any of the talkers. The recording means were less elaborate than those employed in the later investigation, and the principal interest in the preliminary test lies in the fact that the results have shown themselves in good agreement with those obtained later with different talkers and widely different circuit conditions.

The conversations which provided the material for the main part of this study were those which took place between male talkers on a circuit used as a tie line by the Western Electric Company and running from the company's Hawthorne plant at Chicago, Illinois, to the New York office. This is a circuit which is used wholly for transaction of company business, and most of the users hold at least minor executive positions in their organizations and have a background of scientific or formal business training. It is recognized by the authors that this somewhat restricted class of talkers may not be representative of telephone users in general. It is also recognized that the manner of telephonic conversation may be different for long distance and local calls. However, analyses of data from other tests which have been made on the tie line, involving a wide range of delays and types of voice operated devices, have indicated that the talkers endeavored to converse in the same manner regardless of the circuit configuration.

[1] A *lockout* is the simultaneous blocking, by voice-operated devices, of both directions of transmission of a two-way communication system. For a discussion of this, and other possible definitions, see the companion paper by Mr. A. W. Horton, Jr.

The Western Electric circuit is a four-wire 19-gauge H-44 circuit [2] 817 miles long, with a 1000-cycle time of transmission of 0.043 second. Normally there is an echo suppressor at Pittsburgh, which is approximately at the midpoint of the circuit. In connection with other tests which were going on at the time, the normal echo suppressor was removed, and the circuit was looped via Bell Telephone Laboratories where artificial (acoustic) delay circuits and two echo suppressors were inserted to simulate two tandem circuits, each with an echo suppressor at its midpoint. The extra equipment introduced no additional attenuation or frequency discrimination.

Recording Methods and Mechanisms

All of the recording was done by mechanical means controlled by engineers who observed the progress of the conversations. The preliminary data on local calls were obtained with the aid of an inked-roller paper-tape recorder of a type formerly used in telegraph studies. This machine had only two recording traces and was not adapted to run at high speed, thus limiting the amount and accuracy of the information obtainable. In view of the limited amount of data and its relative lack of precision compared to the main body of data it does not appear profitable to enter into a further description of the early recording means.

The principal part of the improved recording mechanism was a six-string rapid-record oscillograph of the type already described in the Bell System Technical Journal.[3] The several strings of this machine were energized by speech power from the two talkers and by energy from an oscillator under control of the echo-suppressor relays. This arrangement is indicated in Fig. 1. The machine was started at the beginning of each call to be observed and ran continuously at a speed of about 20 feet of recording paper per minute. This resulted in a complete pictorial record of the conversational interchanges. These records are well adapted to measurement of the essential time relations, but do not lend themselves to reproduction of the original conversations. Operation of the echo-suppressor relays is also shown on the oscillograms, but analysis of this information is outside the scope of this paper.

To facilitate inspection of the speech traces the voice energy from the circuit was routed through quick-acting automatic volume controls which permitted the weak beginnings and endings of words to be

[2] The designation H-44 means 44 millihenry loading coils spaced 6000 feet apart.
[3] "An Oscillograph for Ten Thousand Cycles," A. M. Curtis, Vol. XII, No. 1, pp. 76–90.

observed without producing excessive amplitudes of the recording strings during the strong parts of speech. These devices, as used, distorted the recorded envelope of the speech sounds considerably, but assisted materially in showing just where speech traces started and stopped. Noise occasioned little difficulty in this study. When observable, the traces of the noise were so characteristic that little confusion with speech waves resulted.

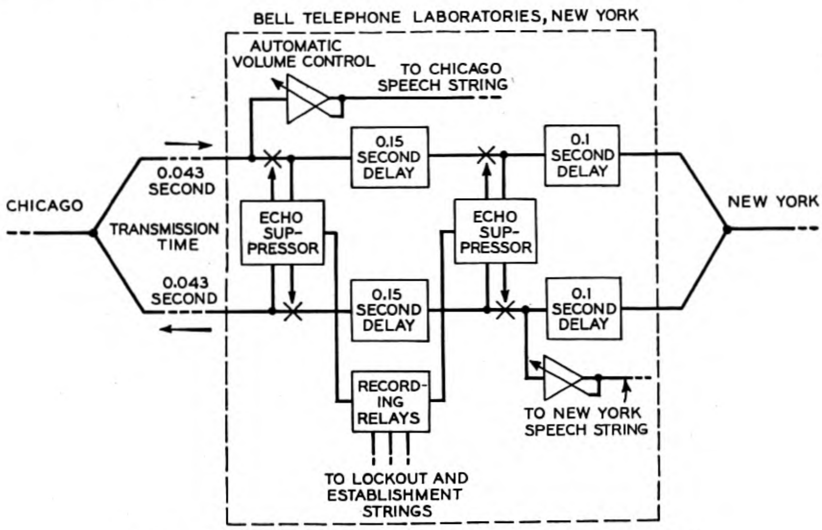
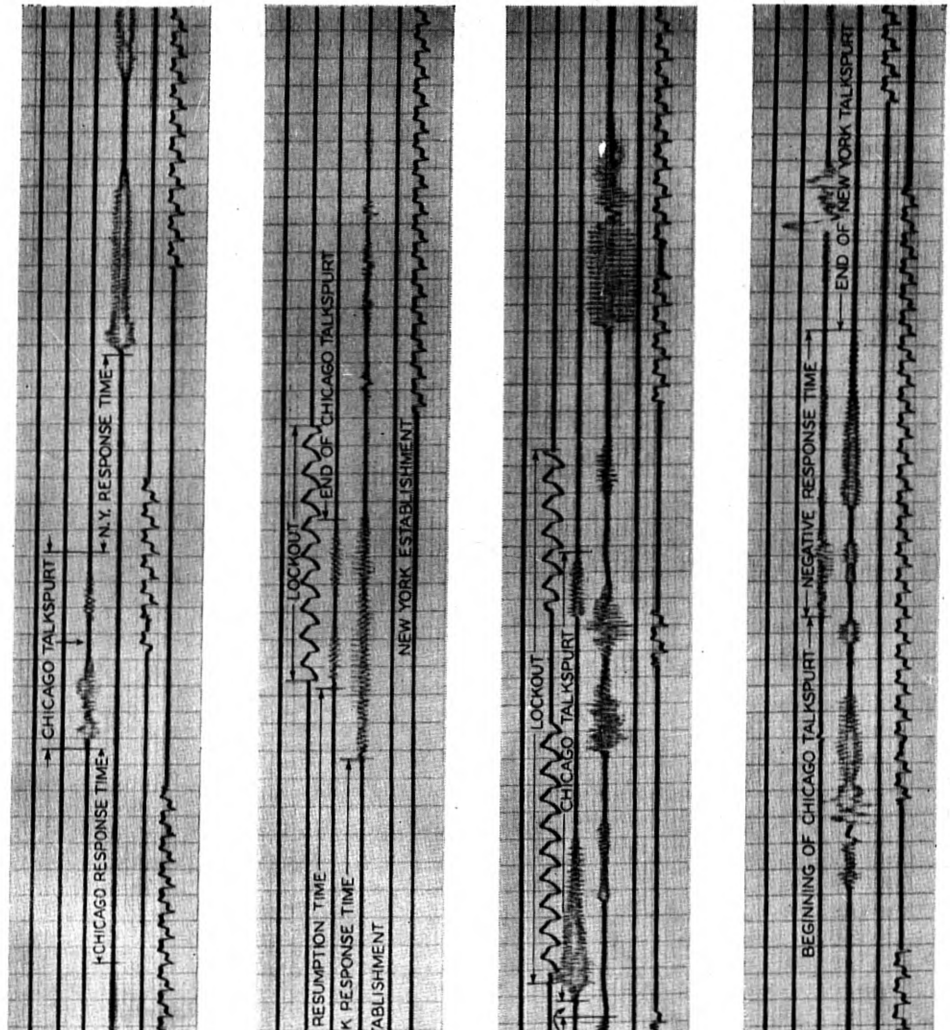


Fig. 1—Connections to New York–Chicago tie line to obtain oscillograms of conversations.

Some observations of response and resumption time were lost when double talking occurred, because echo suppressor operation introduced appreciable loss into one side or the other of the recording circuit.[4] High gain in the automatic volume control and high speech volumes, however, permitted many of such instances to be properly recorded. There is little reason to believe that the instances lost were frequent or that they differed in any particular regard from those recorded; such instances occurred only in the event of double talking involving weak speech by the responding talker.

Instances in which double talking was clearly recorded required a certain amount of arbitrary judgment to decide whether the response was induced by a resumption pause or represented a negative response time. Usually the structure of the conversation was evident, but it is recognized that in some cases there is room for a legitimate difference of opinion.

[4] This loss, while considerable, was not nearly so great as that introduced into the transmission path by the echo suppressor operation.



a b c d

Fig. 2—Typical sections of oscillographic records.

a. Circuit reversals. New York completed talkspurt, heard Chicago's reply, and began another talkspurt.

b. Reply by New York during pause by Chicago caused lockout. New York gained control of the circuit.

c. Short reply by Chicago during pause by New York caused lockout. New York regained control of the circuit.

d. Negative response time. Chicago replied before the completion of New York's talkspurt.

A few samples from the original oscillograms are shown in Fig. 2. The speech energy in each sample is shown on traces 3 and 4 counting from the top down, the upper being from Chicago and the lower from New York. The cyclic waves on traces 2, 5 and 6 indicate respectively lockout, establishment by Chicago and establishment by New York.[5] These waves were obtained from an oscillator which was concurrently used to drive an escapement-type electric clock for measuring the total call duration.

The top oscillogram was selected to show the simplest type of conversational interchange. It will be seen that New York had been talking but had reached the end of his talkspurt as marked on the film. Approximately 0.4 second later Chicago responded, his talkspurt apparently consisting of three syllables, whereupon after a further time of about 0.35 second New York responded and continued talking. The second film was selected to show a less simple type of interchange wherein a long pause within a talkspurt prompted the listener to reply. In this instance the times were such that a lockout resulted. Since the remainder of the talkspurt by the original talker, Chicago, was short and the responding party, New York, continued talking, the circuit was established in New York's direction after the lockout. In the third oscillographic strip Chicago attempted to interrupt, and a short pause by New York permitted lockout to occur; Chicago did not gain control of the circuit. This is an example of concurrent talkspurts, both of which were included in the data. The fourth example was chosen to illustrate a negative response time. In this case Chicago began to reply before the end of New York's talkspurt; no lockout occurred, but the first part of the reply was inaudible to New York due to continued establishment of the circuit in the opposite direction.

It may be noted in Fig. 1 that speech from Chicago was recorded 0.25 second before it was heard by New York and that speech from New York was recorded 0.193 second before it arrived at Chicago. Likewise the beginning of each response did not occur at the time shown on the oscillograms but at a time previous by the delay from the talker's position to that of the recording means. To obtain the response times as previously defined each apparent response time was given an appropriate time correction.

Data Obtained

The more detailed observations were made on fifty-one calls with a total recorded duration of a little over 13,000 seconds. At the recording speed of 20 feet per minute this resulted in about 4400 feet of

[5] An establishment by a talker is said to occur when his speech energy has gained control of all voice operated equipment in his transmission path.

oscillograms. In all cases recording began at the start of the call, but in some instances recording was stopped before the termination of the call due to lack of recording paper in the oscillograph. The oscillograms, ranging in length from 29.6 to 660.8 seconds, represented observations on calls whose mean duration was 430.5 seconds. The speed of recording was such that the time intervals under observation could readily be measured with a precision of $\pm$ 0.005 second. The conversational elements were measured with this precision and listed in their order of occurrence for each call. The records for all calls were

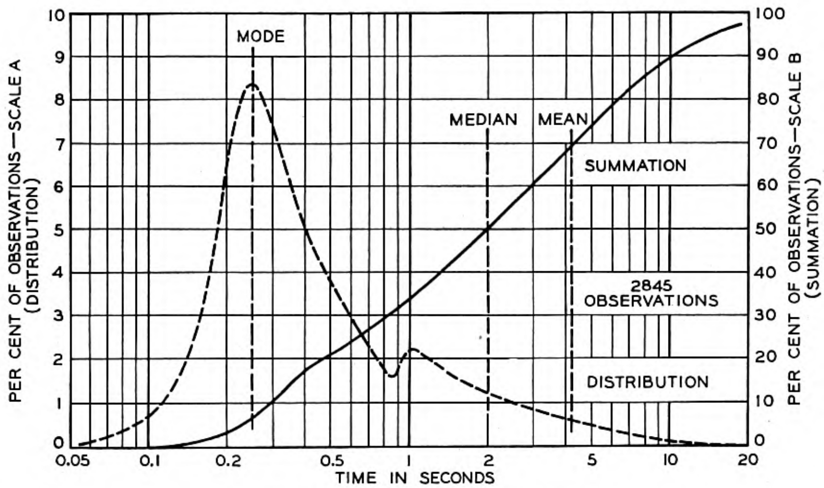


Fig. 3—Lengths of talkspurts.

then consolidated and retabulated in terms of the number of instances of each element whose duration could be included within each of a regular progression of time increments. For all three items of data time cells 0.10 second wide were chosen. The data, when thus cellularized, provided the basis for the construction of histograms from which the time-distribution curves were obtained. These distribution curves and their respective summation curves are given in Figs. 3, 4, and 5. Some of the statistically significant quantities [6] are tabulated on the opposite page. The values are time intervals in seconds.

Since most telephonic speech syllables are shorter than 0.3 second the modal value of 0.25 second for the length of talkspurts makes it clear that monosyllabic replies are by far the most numerous. From

[6] The *mode* is the value which occurs most frequently, i.e., the peak of the distribution curve.
The *median* is that value above and below which equal numbers of observations lie.
The *mean* is the arithmetic average of all the values observed.

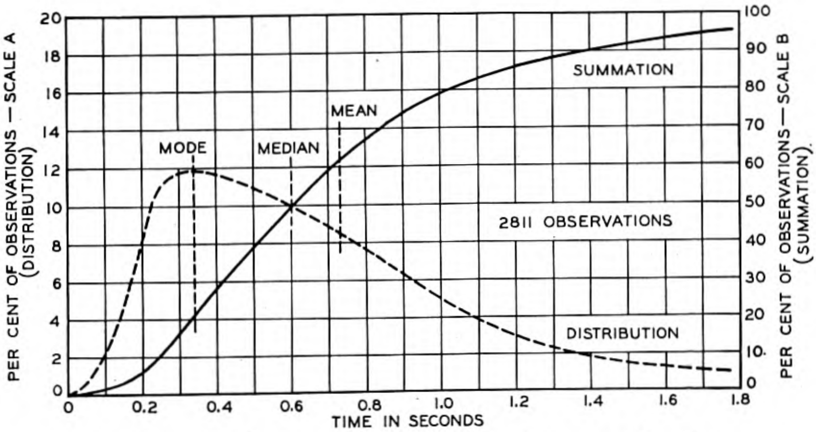


Fig. 4—Lengths of pauses within talkspurts, i.e. *resumption times.*

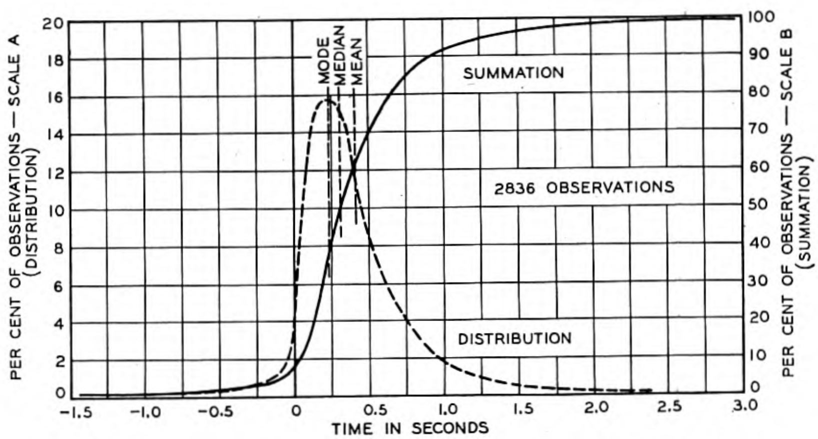


Fig. 5—Lengths of pauses between talkspurts, i.e. *response times.*

	No. of Obs.	Min.	Mode	Median	Mean	Max.
Talkspurts	2845	0.09	0.25	2.00	4.14	143.82
Resumptions	2811	0.05	0.34	0.60	0.73	4.86
Responses	2836	−3.95	0.24	0.32	0.41	5.04

Fig. 3 it may be seen that these, in conjunction with terse replies or questions under one second in duration, constitute about a third of the talkspurts. There were, however, a few very long talkspurts: 27 exceeded 30 seconds, and of these 2 were over 120 seconds long. During the longest talkspurt, which was 143.82 seconds, there were 62 resumptions following silent intervals ranging from 0.34 to 4.04 seconds.

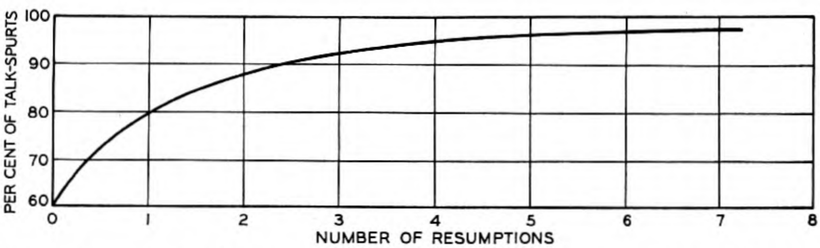


Fig. 6—Percentage of talkspurts containing a number of pauses equal to or less than a given number.

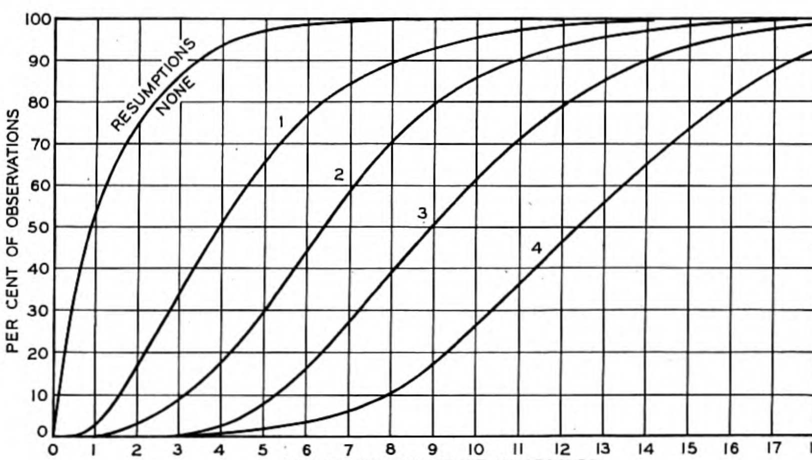


Fig. 7—Lengths of talkspurts containing a given number of pauses.

Figs. 6 and 7 show the results of analyses made to determine how frequently pauses occur within talkspurts and how the number of pauses varies with length of talkspurt. In Fig. 6 the percentage of talkspurts having a number of resumptions equal to or less than a given value is shown. It will be seen that about 60 per cent of the talkspurts contain no pauses; these comprise all the monosyllabic replies and about half the longer ones. A further analysis, shown in

Fig. 7, wherein talkspurts having a given number of resumptions are sorted according to length, indicates that almost all talkspurts exceeding 6 seconds in length contain resumptions. On the average, resumptions seem to occur about once every three and one third seconds in the longer talkspurts. The aggregate of all the resumption pauses within talkspurts amounts to about 17 per cent of the total talkspurt time.

It will be recognized that in obtaining the curves of resumption times in Fig. 4 a certain amount of arbitrary judgment must be exercised. As stated previously, the temporary absence of deflection of an oscillographic trace showing speech energy was regarded as evidence that the talker was pausing. Some assistance in determining whether or not speech energy was present was given by the trace showing the operation of the corresponding echo suppressor. The comparatively slow change in amplitude at the beginning and ending of syllables renders this determination more difficult as shorter and shorter pauses are considered. However, those shorter than about 50 milliseconds within connected speech must be observed with so much amplification that they tend to be obscured by noise on even a very quiet line. From a knowledge of the characteristics of the volume controls and echo suppressors used it is estimated that Fig. 4 represents pauses greater than 50 milliseconds during which the amplitude is lower than about 0.2 per cent of the maximum amplitude.

Conclusion

Telephonic conversation has been arbitrarily defined in terms of a few elements whose specification serves to completely describe its progress in time. These elements have been measured on a particular telephone circuit and the measurements have been presented in the form of distributions which approximate the probability of their occurrence.

A preliminary investigation under quite different conditions gave results remarkably close to those found in these more extended tests, suggesting that the conversational elements to be found throughout the aggregate of telephone users may not be materially different from those found in this investigation.

Radioactivity—Artificial and Natural [1]

By KARL K. DARROW

RADIOACTIVITY is a world-famous word relating to a world-famous subject. In general, when a statement of this sort is spoken, it is more than likely to be foolish; for specialists are altogether too addicted to imagining that their special interests are of world-wide concern when perhaps not fifty thousand people have even heard of them. With respect to radioactivity, though, the statement *is* correct. It would have been difficult indeed for any literate person to miss making the acquaintance of this word, in any year since 1900. I might say that radioactivity has been the best-advertised topic in modern physics—and this is not to say that it has been over-advertised! It is in fact the only part of modern physics which has received something approaching its due renown. Such good fortune cannot of course be altogether due to the fundamental values of the subject. A great part of the fame of radioactivity comes from medical applications and even more from medical hopes, and some from incidental things, such as the tragic end of one of its great students and the sex of two others. Still it is a matter for rejoicing that whatever the reasons may be, one portion of physics now enjoys its proper quota of the glory to which so many others are entitled.

The discovery of radioactivity took place in 1896. Quite a number of things of the highest importance to physics—and to humanity at large—were begun between 1895 and 1900, and of these the study of radioactivity was the second. The study of X-rays was the first. The second was commenced only because the first had been, and therefore I speak of the first. Imagine a tube containing air and a couple of electrodes a few inches apart, and suppose that you have a battery which can supply a durable current at ten thousand volts or more, and an air pump as well. If the air is at atmospheric pressure, the ten thousand volts can be applied between the electrodes and nothing will happen. If with the pump you now reduce the pressure of the air to about a thousandth of the atmospheric value, the air which remains in the tube will become very luminous and splendid. If next you re-

[1] A lecture sponsored by the New York Electrical Society and by the American Institute of Electrical Engineers. Delivered before the former on January 12, 1938. Scheduled for presentation to the latter at its Northeastern District Meeting in Lenox, Massachusetts, on May 19, 1938.

duce the air-pressure by yet another ten-fold, the splendor will fade out, but now the glass of the tube itself, in the region opposite the negative electrode, will be shining with a pale green glow. This too is a beautiful sight, but decidedly not one to be enjoyed for a long time at close range, for it is attended by invisible rays very dangerous to health and even life. These are the X-rays.

Many people have heard that Roentgen discovered the X-rays because he kept some photographic plates in a box which happened to lie near the tube, and found one day that the plates were fogged. It is true that he did observe the fogging of plates by the rays; it is true also that for years afterward, people were telling in various parts of Western Europe and America how they too had noticed that their plates were spoiled when left by accident in the neighborhood of discharge-tubes, but unluckily they had only felt annoyed and had resolved to keep their next batches of plates in safer places. However it was something else that led Roentgen to the discovery. He had in his laboratory some sheets of phosphorescent substances; and he found that whenever one of them was in the neighborhood of the tube it would shine; and what was more, *it would shine even when hidden from the tube by a sheet of black cardboard*. The X-rays (as he presently named them) were able to pierce substances opaque to light, and to cause phosphorescent substances to shine. Roentgen very soon discovered other properties of the rays, but these were the earliest. Moreover the greenish glowing of the glass in the X-ray tube itself resembles the light of phosphorescence; so, here were two apparent connections between penetrating X-rays on the one hand, and phosphorescence [2] on the other.

Now we come to radioactivity. There was a man in Paris whose attention was caught by these facts, and his name was not Curie. Curie is the second great name in the story of radioactivity; the first is Becquerel. I put down his first name (Henri) as well, for Becquerel—like Curie and Bernoulli and Darwin and others—is the name of a dynasty of scientists, of which Henri was the third. Henri Becquerel seems to have reasoned [3] after this fashion: "X-rays and phosphorescence are found together; therefore, wherever there is phosphorescence, there may be rays like X-rays." So he took photographic plates and wrapped them in dark paper, and then he took one phosphorescent substance after another and (after making them luminous by exposing them to light) laid them in succession beside the plates, and after an interval looked to see whether there had been fogging. Time after

[2] Or fluorescence: a careful distinction is drawn between phosphorescence and fluorescence by specialists, but need not detain us here.

[3] The idea is, however, ascribed to Henri Poincaré by Marie Curie,

time the result was completely negative, but at last he came upon a chemical compound of the element *uranium* which was phosphorescent and which fogged the plate. It is not recorded that he shouted "Eureka!" but he had as good reason so to do as Archimedes. He had discovered the first-to-be-known example of radioactivity.

Now comes the strange and paradoxical part: Becquerel had arrived at his great discovery by following a false clue. There is really no connection whatever between radioactivity and phosphorescence, and it was purely an accident that a compound which was phosphorescent had happened to contain an element which was radioactive. In trying to make a simile for what then happened, I have adopted the rather frivolous comparison which follows. Suppose that you were to meet a man who was wearing a blue serge suit, and notice that he was speaking a foreign language—Swedish, let us say. For some reason this would interest you particularly, and you would decide to look for other examples of people speaking Swedish. You would begin by reasoning that "Swedish speech was associated with a blue serge suit, and therefore any man who is wearing blue serge may speak Swedish." You would then listen to everyone whom you passed in the street who was wearing blue serge, and the first few whom you heard would prove to be speaking English. This would prevent you from believing that a blue suit necessarily entails the speaking of Swedish: but you might continue nevertheless, and eventually find another man who was wearing blue serge and speaking Swedish. Now if you were like some people, I am afraid you would send a communication to a scientific journal, announcing that it is a principle that everyone speaking Swedish is wearing a blue serge suit. But not if you were like Becquerel! If you were like Becquerel you would trail the man for weeks; and sooner or later you would come upon him wearing a grey suit or a brown one, and still he would be speaking Swedish. In the course of time you would doubtless come upon other people who never wore blue serge and yet spoke Swedish. Finally you would realize that it was just a piece of luck that you had happened to discover a man speaking Swedish, by making the fallacious assumption that all such men wear blue. Now in this case of Becquerel's, the phosphorescence was only a feature of the clothes which the uranium happened to be wearing, or more literally, the chemical compound in which it was involved. But the radioactivity was a feature of uranium itself, and that is what Becquerel proceeded to prove; first by testing various other chemical compounds of uranium which were not in the least phosphorescent, and then by testing the pure uncompounded metal itself.

Uranium, then, is a radioactive element. But it is not the only one; there were numerous others, even in the days before the physicists had started making new ones. This is where the elder Curies enter the story: Pierre and Marie Curie, in 1898. First they measured the activity of uranium, pretty carefully. Then they started measuring the activity of various minerals containing uranium, and they found too much: these minerals were more active than by virtue of their uranium content alone, they should be. The Curies suspected that some other radioactive element was lurking in the depths, and they undertook to get it out. This was of course a chemical problem primarily, and as a matter of fact, their Nobel prize was the chemistry prize, and quite rightly. Eventually they isolated their new element, or rather, two of them, which they named "polonium" and "radium." Having at last got their radium and weighed it, they found that it amounted to only two parts in a hundred million (by weight) of the rock from which they had extracted it. They required three tons of the rock, in order to get one one-hundredth of an ounce of the radium. Two parts in a hundred million! and yet, while it was still dispersed in that almost incredible scantiness through the rock, they had already been able to detect it! This is the point which I most wish to bring out, at this stage. A radioactive substance is far more easy to detect than any which is not. It is like salt in food, and the radioactivity is like the flavor of the salt, which shows the presence of a dash so insignificant that anything else in the food would go untasted if it were equally rare. Fortunately for us the instruments which are used to detect a radioactive body are not our tongues, but apparatus of a much less vulnerable kind.

Now I mention only one name before reaching the recent developments, but this the greatest name of all: RUTHERFORD. Rutherford was the first to understand radioactivity—the first to prove the contemporary atom-model—and the first to achieve transmutation. Any one of these achievements by itself would have secured undying glory to its author, but this great man made three. As lately as two years ago I wrote in a book that every leading figure in the history of transmutation was still living and still ardently at work. As lately as last October I could have repeated that, but now the Master is gone—quite suddenly gone in the fullness of his powers. This lecture is a memorial to Rutherford, not because it was expressly so designed, but because any lecture on the new radioactivity or on the old involves so much of his thought and so much of his work that it would be reduced to a few incoherent bits if everything not traceable to Rutherford should be left out.

The first achievement of Rutherford in this field was to identify the rays emitted by radioactive bodies. He identified three kinds, and gave them the names which they still bear and assuredly always will: *alpha*, *beta* and *gamma* rays. The last-named (which are of the nature of light) are the ones whereby radioactivity was first detected, for they are the ones which fog the plates and produce the phosphorescence outside of a rather narrow space just around the radioactive substance itself. They are also the ones responsible for the great work already done in medicine by radioactive bodies, and on which (I am told) there is great reliance for the future. If this were a medical lecture the gamma-rays would require most of its content; but as it is not, I leave them with this brief allusion, and turn to the others. The beta-rays are electrons, which may be of either sign (Rutherford, like the rest of the world, was acquainted only with the negative ones until five or six years ago). The alpha-rays are also charged particles, much heavier than electrons; I shall be defining them more exactly before long. The beta-rays and the alpha-rays, and for that matter the gamma-rays as well, are detected by very ingenious devices of which most types are electrical, though the particular type which supplies the photographs seen in this lecture is not.

Now at last I exhibit the list of the radioactive elements.

This list (Fig. 1) is none other than the veritable Table of the Elements itself! *Of all the known elements there now remains just one of which no radioactive form has yet been discovered or invented.* Hydrogen is the exception (the listener may say "Of course!" but it is not excluded that some day a radioactive type of hydrogen may be produced). At the end of the list stands uranium, the first of the radioactive bodies to be discovered. It has stood there ever since Mendeleieff set up the table in this fashion, but actually it now must yield its pride of place, for physicists have lately created radioactive elements which lie beyond it. I have though gone ahead too rapidly in speaking of these already. Once more let me state the marvelous fact that of all the known elements, every one but hydrogen exists in a radioactive form, or perhaps in more than one.

In speaking of "forms" I have been alluding to something which the Table as it stands in Fig. 1 does not make clear. Everyone recognizes the "chemical atomic weights" there appended to the symbol of each element. If an element has only one kind of atom, this figure is the actual mass of the atom, expressed in terms of a unit which I will presently define. There are such elements; beryllium and fluorine, sodium and aluminium are examples. Most elements, however, have two or more kinds of atoms differing in mass. Thus, in Fig. 1, the

PERIODIC TABLE OF THE ELEMENTS

(Values of atomic weights taken from the seventh Report of the Committee on Atomic Weights of the International Union of Chemistry; G. P. Baxter, *et al.*, *J. Am. Chem. Soc.*, **59**, p. 219)

I	II	III	IV	V	VI	VII	VIII			O
1 H 1.0078										2 He 4.002
3 Li 6.940	4 Be 9.02	5 B 10.82	6 C 12.01	7 N 14.008	8 O 16.000	9 F 19.00				10 Ne 20.183
11 Na 22.997	12 Mg 24.32	13 Al 26.97	14 Si 28.06	15 P 31.02	16 S 32.06	17 Cl 35.457				18 A 39.94
19 K 39.096 29 Cu 63.57	20 Ca 40.08 30 Zn 65.38	21 Sc 45.10 31 Ga 69.72	22 Ti 47.90 32 Ge 72.60	23 V 50.95 33 As 74.9	24 Cr 52.01 34 Se 78.96	25 Mn 54.93 35 Br 79.916	26 Fe 55.84	27 Co 58.94	28 Ni 58.69	36 Kr 83.7
37 Rb 85.48 47 Ag 107.880	38 Sr 87.63 48 Cd 112.41	39 Yt 88.92 49 In 114.76	40 Zr 91.22 50 Sn 118.70	41 Nb 92.91 51 Sb 121.76	42 Mo 96.0 52 Te 127.61	43 53 I 126.92	44 Ru 101.7	45 Rh 102.91	46 Pd 106.7	54 Xe 131.3
55 Cs 132.91 79 Au 197.2	56 Ba 137.36 80 Hg 200.61	RARE EARTHS 81 Tl 204.39	72 Hf 178.6 82 Pb 207.21	73 Ta 180.88 83 Bi 209.00	74 W 184.0 84 Po	75 Re 186.31 85—	76 Os 191.5	77 Ir 193.1	78 Pt 195.23	86 Rn 222
87—	88 Ra 226.05	89 Ac	90 Th 232.12	91 Pa 231	92 U 238.07					

RARE EARTHS

57 La 138.92	58 Ce 140.13	59 Pr 140.92	60 Nd 144.27	61	62 Sa 150.43	63 Eu 152.0	64 Gd 156.9
65 Tb 159.2	66 Dy 162.46	67 Ho 163.5	68 Er 167.64	69 Tm 169.4	70 Yb 173.04	71 Lu 175.0	

Fig. 1

pigeonhole for hydrogen should contain three mass-values; that for helium, two; that for tin, no fewer than ten. It would make the table impossibly crowded to print them all in this way, and consequently I have broken it up into sections, of which Fig. 2 represents the first six elements.

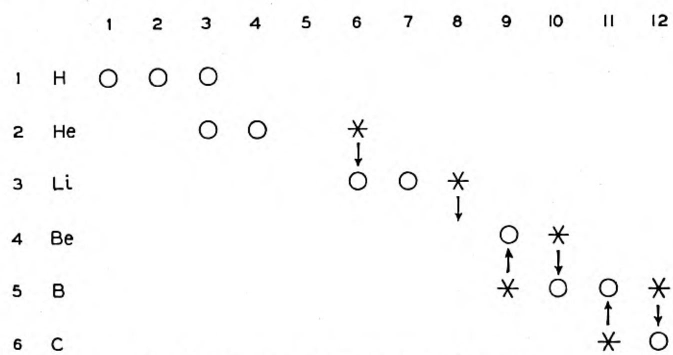


Fig. 2—Isotopes of the first six elements.

In this figure each element has a row to itself, and each value of mass has a column to itself, and each circle represents a stable kind of atom. I now introduce the technical term "isotope" to distinguish the different kinds of atoms common to a single element. Hydrogen, you see, has three stable isotopes (there is some doubt about the stability of the third, though none about its existence); helium two (again there is doubt about the stability of one); lithium two, beryllium only one, boron two, and carbon two of which the second will appear in the next figure. The unit of mass is a very small amount, about $1.67 \cdot 10^{-24}$ of one gram. I do not pause to give it as accurately as I might, for we are not going to be concerned with very exact mass-values in this talk. The masses of the isotopes are not exactly integer multiples of this unit; for instance, those of the three kinds of hydrogen atoms are 1.008, 2.016 and 3.017. The departures from integer multiples are, however, small, as you see in these three cases. Small as they are, they are mightily important; but it is permissible to ignore them for the purposes of this lecture, and I am going to ignore them from now on. I will, however, speak of the integers at the heads of the columns as "mass-numbers" rather than "masses."

Since the isotopes of an element differ in mass, what is it then that they have in common? I answer this question by describing Rutherford's second great achievement, the "nuclear atom-model." Rutherford was the first to prove that the atom consists of a positively-charged nucleus surrounded by a swarm of negative electrons. The nucleus is much more massive than the electrons, and this is one of the reasons for comparing the atom with the solar system, in which the sun is much more massive than the planets which perpetually swing in orbits around it. A less hackneyed and newer simile is that of Bragg, just now, by the way, appointed as Rutherford's successor in the Cavendish chair at Cambridge, who likens the atom to a man's head with a swarm of gnats buzzing around it. Normally—that is to say, when the atom is complete and electrically neutral—the negative charges of all the electrons put together just balance the positive charge of the nucleus. If Z be used to stand for the number of electrons in the normal neutral atom, and $-e$ for the charge of the negative electron, then $+Ze$ is the amount of the charge on the nucleus. Z is called the "atomic number" of the element in question.

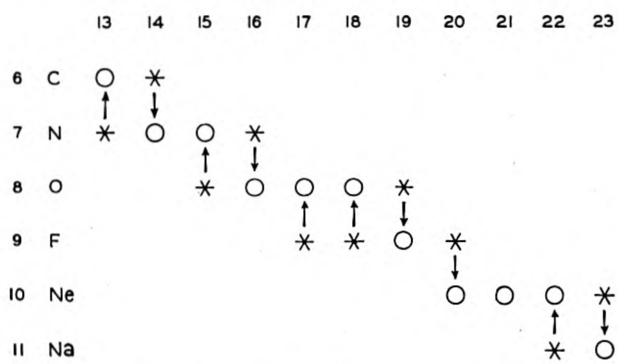


Fig. 3—Isotopes of the elements numbered 6 to 11.

This it is, of which all the isotopes of any one element have the same value. This it is which distinguishes an element, and is common to all of the different atoms of that element whatever their masses may be. For hydrogen it is 1; for helium 2; for lithium 3; for uranium 92. Each row in Fig. 2 and Fig. 3 is marked on the left not only with the chemical symbol of the element to which the row belongs, but also with the atomic number thereof.

Radioactivity is a feature of the nucleus. This accounts for some of its remarkable aspects, which greatly surprised the world of physicists and chemists when they were first established. Being a quality of the nucleus, it varies from one isotope[4] to another of any element, much more drastically than does the mass. Being a quality of the nucleus, it is immune to the physical state of the atom—*i.e.* it is the

[4] Isotopes were first distinguished from each other (by Soddy) by virtue of their differences in radioactivity.

same whether the atom is part of a solid, a liquid or a gas; it is immune also to the chemical state of the atom, *i.e.* it is the same whether the radioactive element is isolated or is part of a chemical compound. It is also immune to heat and to all of the many other agencies which physicists and chemists have at their command.

Radioactivity being a feature of the nucleus, every chemical symbol which I use from now on will refer to the nucleus of an atom and not to the atom as a whole. "Be" will stand for beryllium nuclei, "F" for fluorine nuclei, "Al" for aluminium nuclei. For most elements, though, there are two or more different sorts of nuclei distinguished from each other by their masses, and the symbol must tell us which is meant. The custom is to write the mass-number of the isotope in question as if it were an exponent: H^1 and H^2 and H^3 for the three kinds of hydrogen nuclei, He^3 and He^4 for the two kinds of helium nuclei, Li^6 and Li^7 to distinguish between the isotopes of lithium, and so on. If in addition one wants to remind the reader of the atomic number, one writes it as a subscript before the chemical symbol: ${}_1H^1$, ${}_1H^2$, ${}_2He^4$, ${}_9F^{19}$ and the like. Purists object that either the chemical symbol or the value of Z is superfluous when both are given, but others often like to see them both. And now for some names: there are three nuclei which have names of their own. The Greek words for "first" and "second" are applied to ${}_1H^1$ and ${}_1H^2$; they are the *proton* and the *deuteron*. The name for ${}_2He^4$ is *alpha-particle;* this nucleus is indeed the particle which, as Rutherford discovered long ago, makes up one of the three kinds of rays which radioactive bodies emits, and there never was a greater piece of good fortune in language than that whereby this all-important particle received the name of the first letter of the Greek alphabet, for indeed it is the alpha of modern nuclear physics. And now another reference to masses: the mass of the electron (when not moving extremely fast) is only about .0005 of the mass-unit which is being used throughout this talk, and therefore the mass-numbers at the heads of the columns in Figs. 1 and 2 and others are about as good approximations to nuclear masses as they are to atomic masses, and I shall use them as such.

Now let us notice not only the circles of Figs. 2 and 3, but the stars as well. The stars also stand for nuclei, but these are *radioactive*—or *unstable*, two words which have practically the same meaning when applied to a nucleus. At least one star appears in every row, the first in Fig. 2 excepted. If the figure had room for ninety-two rows, one for each element from hydrogen to uranium, there would appear at least one star in every row below the first, excepting three (atomic numbers 61, 85, 87) for which no isotope either stable or unstable known with certainty and the element itself must still be regarded as missing. (Furthermore there should be at least three more rows numbered 93, 94 and 95, and containing stars but no circles.) This is what is meant by saying that every known element, hydrogen alone excepted, has at least one radioactive form.

Figure 2 shows that at the beginning of the Table of the Elements, the stable types of nuclei outnumber the unstable ones. The preponderance is gradually shifted as Z increases, and Fig. 4 exhibits to us how greatly the radioactive nuclei outnumber the stable ones among the elements of which the atomic numbers range from 81 to 84. Indeed the circle which is lowest and most to the right in Fig. 4 represents the most massive and most highly charged of all the stable nuclei which are known (it is the solitary isotope of bismuth, atomic number 83 and mass-number 209). All the rows after 83 are occupied entirely by stars.[5]

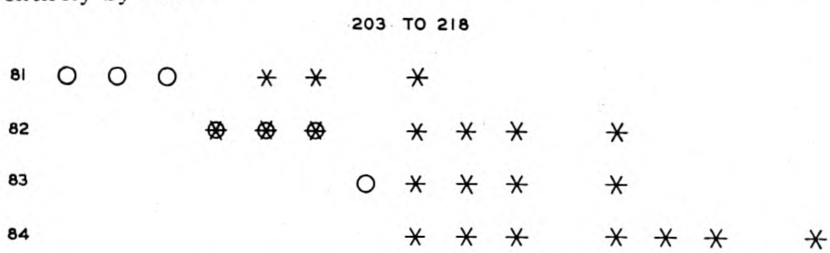


Fig. 4—Isotopes of the elements numbered 81 to 84.

As the title of this talk has already suggested, the radioactive nuclei are of two classes: the "natural" and the "artificial," the types already existing in the rocks of the earth and the types made in the laboratory by physicists employing the art of transmutation. Nearly all of the natural types lie beyond 80 in atomic number, and most of them were discovered in the first fifteen years after Becquerel found the first. Two of them are identical with two of the man-made types. Apart from these two, every one of the artificial types is a creation of the years since 1933. One guesses that while the natural radioactive bodies may be many, the artificial ones must surely as yet be few; how surprising then to learn that while there are some forty of the former, the latter after four brief years already number two hundred and thirty! Unlike the natural ones, these artificial isotopes are sprinkled liberally throughout the whole of the Table of the Elements, from the second onward to the end. Not only in number but in di-

[5] It must though be admitted that some of the heaviest nuclei, though demonstrably radioactive, may exist for hundreds of millions of years before they disintegrate; "instability" is indeed a very relative concept!

versity of mass and charge are the artificial radioactive bodies now outstanding by far.

These artificial examples forming now so large and important a group among the radioactive nuclei, I make a digression to speak of some of the transmutations from which they are derived. The art of transmutation is already so huge a subject that the digression must be severely limited if ever we are to come back to radioactivity. I must therefore make only a passing allusion to the fact that the first of the new radioactive nuclei were made by bombarding various light elements with very energetic alpha-particles. Here the second Curie generation must be introduced, for the daughter and son-in-law—Irene Curie and Frederic Joliot—of the first Curie pair were the ones who made this discovery. (It was not their entry into the field of radioactivity, they having already studied natural radioactive bodies for a number of years).

Returning to Figs. 2 and 3, notice that many of the radioactive isotopes lie just one step to the right of stable isotopes: Li^8, Be^{10}, B^{12}, C^{14}, N^{16}, O^{19}, F^{20}, Ne^{23} are the examples found in these two pictures alone. It seems as though they might differ from their neighbors on the left—Li^7, Be^9 and so forth—by possessing an extra particle of mass (approximately) 1 and charge zero. If only one could find such particles roaming freely about in Nature, might one perhaps succeed in adding them to the stable nuclei of lithium and beryllium and boron and the other elements, and so produce these radioactive nuclei?

Such particles may indeed be found roaming about in Nature, but not of their own volition. These "neutrons"—for such is their name—must themselves be set free by the art of transmutation. Free neutrons were first produced by bombarding certain elements with alpha-particles; the discovery was an international one, and its story is interesting, but to keep this digression within bounds I must again content myself with giving the names—Bothe and Becker in Germany, Curie and Joliot in France, Chadwick in England—of those who carried it through its consecutive stages from first intimation to triumph. More than a hundred different ways of freeing the neutron are already known, but of all this diversity I will take one only, which consists in projecting deuterons against deuterons.

The "deuteron-deuteron reactions"—D-D reactions for short—are produced by applying high voltage to deuterons (emerging from a discharge-tube containing heavy hydrogen, in which some of the atoms are divested of their electrons and the nuclei are left bare) and then directing them across a vacuum against a target containing other deuterons. (The target may be some solid compound of heavy hydrogen, such as ice in which plenty of the hydrogen atoms belong to the isotope H^2; or it may be gaseous heavy hydrogen). The high voltage is required, so that the impinging deuterons may override the electrostatic repulsion between the positive charges which they bear and the positive charges of the deuterons waiting in the target, and come into contact with these last. Generally in transmutation, "high voltage" signifies volts by the millions. These particular reactions are, however, among the easiest to produce, and with less than a hundred thousand volts it is quite possible to liberate neutrons at such a rate that their peculiar qualities can be well studied. (One reaction indeed has been detectably produced at 8000 volts, a figure so low that it arouses speculation as to what the course of physics might have been if the second isotope of hydrogen had been discovered say thirty years ago.)

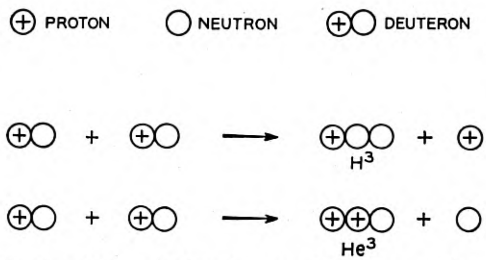


Fig. 5—Scheme of the deuteron-deuteron reactions.

To explain what is actually observed to happen, I ask the listener to imagine the deuteron as a composite of a proton and a neutron, as it is exhibited in Fig. 5. With this image in mind, one might well expect that when deuterons are hurled with great energy and speed against a plate of matter containing massive nuclei—lead, for instance—they would be broken in two. This has been sought for but apparently does *not* happen, showing that we must keep our imaginations under continual check by experiment. What *does* happen is displayed, for the impacts of deuteron against deuteron, in Fig. 5. It seems that one deuteron is after all broken in two, but only under the condition that either its component proton or its component neutron adheres to the other. Another metaphor: one deuteron snatches either the proton or the neutron away from the other, leaving the abandoned neutron or proton to go free. Both of these descriptions are too figurative, but what is certain is this: from the scene of such impacts, particles of all the four kinds shown to the right of the arrows in Fig. 5 are observed to be proceeding. The labels show (what should already be obvious) that the newborn particles of mass 3 are isotopes of hydrogen or helium, according as they contain two neutrons and one proton or two protons and one neutron. I now show pictures to support these statements.

In Fig. 6 the apparatus is shown in a sketch: the cloud-chamber or expansion-chamber of C. T. R. Wilson, being the hollow cylinder which is shown below in axial section, its top being a glass plate and its bottom a piston-head which can be pulled very suddenly downward

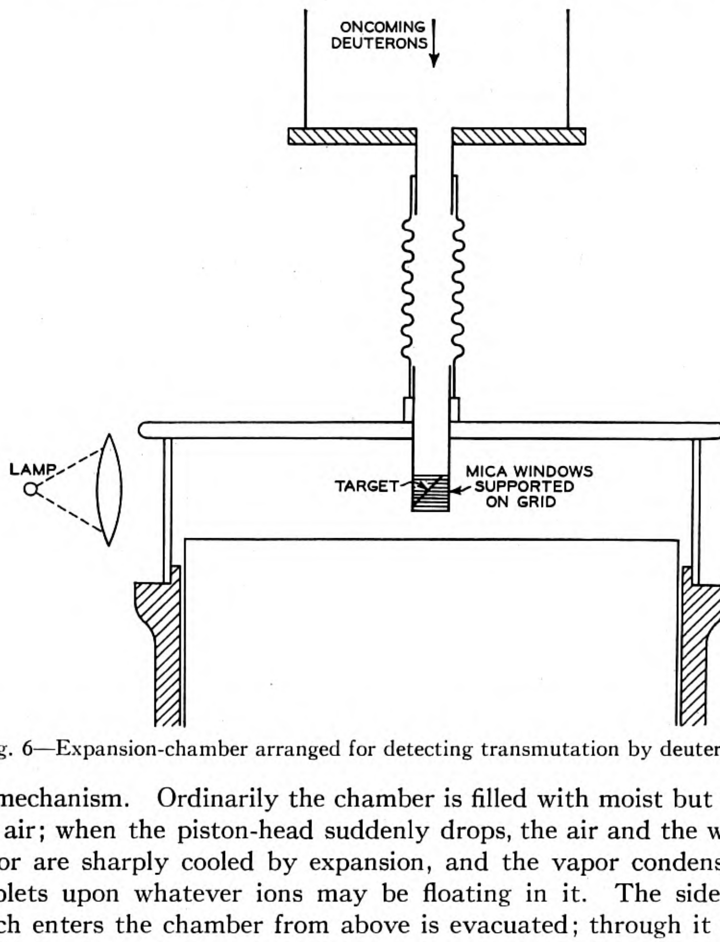


Fig. 6—Expansion-chamber arranged for detecting transmutation by deuterons.

by mechanism. Ordinarily the chamber is filled with moist but dustless air; when the piston-head suddenly drops, the air and the water-vapor are sharply cooled by expansion, and the vapor condenses in droplets upon whatever ions may be floating in it. The side-tube which enters the chamber from above is evacuated; through it come the impinging deuterons, to make their impacts upon the target at the knob-like closed end of the tube. The wall of the tube, thin as it may be made, is too thick to allow the deuterons to emerge into the air of the chamber. One might well expect that *a fortiori*, any new particles born out of the transmutation would be too slow-moving to pierce the wall; but many of these particles are much more energetic than the impinging deuterons themselves, for they draw upon a reserve of energy stored up in the nuclei.[6] They shoot through the wall into the air of the cloud-chamber itself, and if they are charged, they make long trails of ions along their paths. The expansion is then produced and the water-vapor, condensing upon these ions, makes trails of droplets which are the paths made visible.

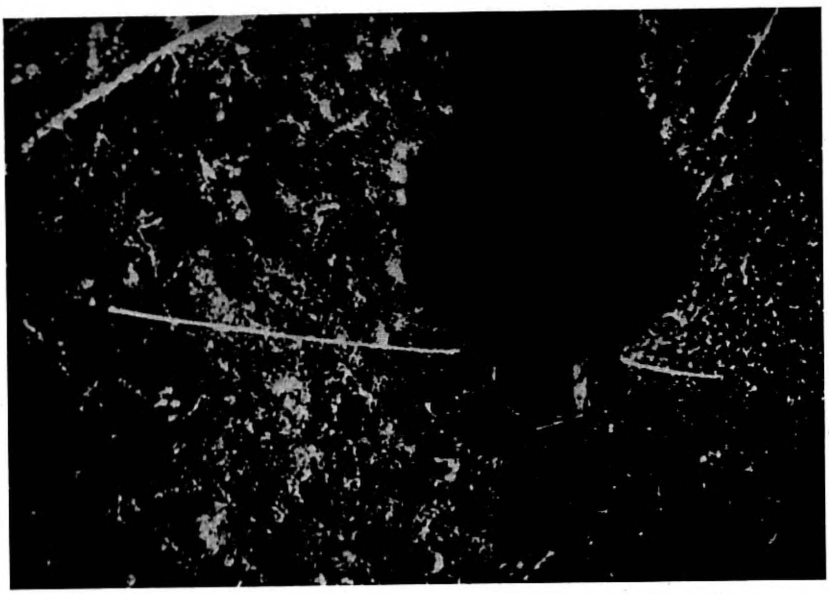


Fig. 7—Tracks of a proton and a H^3 nucleus resulting from one of the deuteron-deuteron reactions. (P. I. Dee, Cavendish Laboratory; *Proceedings of the Royal Society.*)

Figure 7 exhibits two of these visible paths of "tracks," made by particles which sprang from the scene of the transmutation (inside the knob) in practically opposite directions but with very different penetrative powers, since one of the tracks is seen to be much longer than the other. The long one is the track of a proton, the short one is that of a H^3 nucleus which is a deuteron augmented by a captured neuteron; this picture shows a single example of the upper reaction of Fig. 5. How can physicists be sure that these tracks are due to the nuclei which I have named? This question is far too deep to be answered in this place, and I can only assure the listener that while such pictures by themselves cannot suffice for the proof, an unassailable

[6] In the language employed in chemistry, these are "exothermic" reactions.

proof can be and has been given by other and electrical methods of observing these newborn particles.

But how about the lower reaction of Fig. 6—the one which really concerns us, since all this digression is designed chiefly to exhibit the origin of free neutrons? In Fig. 7 no track appears which can be attributed to either a He^3 nucleus or a neutron; and no such tracks appear in other similar pictures. The absence of He^3 is, however, due to a simple cause; these nuclei are born with insufficient energy to traverse the wall of the tube. To observe their tracks it is necessary to suppress the tube-end, to fill the expansion-chamber with heavy

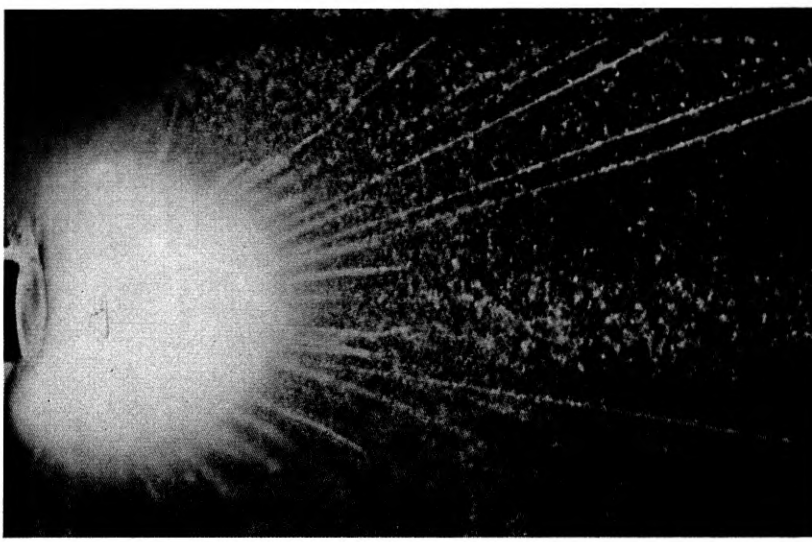


Fig. 8—Tracks of protons, H^3 nuclei and He^3 nuclei resulting from the two deuteron-deuteron reactions. (P. I. Dee and C. W. Gilbert, Cavendish Laboratory; *Proceedings of the Royal Society.*)

hydrogen in the gaseous form, and to project the deuterons directly into it. When this is done, all of the region of the gas which the impinging deuterons can reach becomes completely filled with the ions formed along their many tracks, and appears as a flare on the photograph (Fig. 8). Out of the flare project the tracks of the newborn nuclei. Those which stretch clear across the picture are in part those of protons, in part those of H^3 nuclei born from the first reaction. But in addition one sees a number of short tracks which terminate not far from the edge of the flare itself. These are the tracks of He^3 nuclei—not merely guessed, but proved, to be such.

Where, however, are the tracks of the neutrons? They are not seen upon this picture, nor in any; for neutrons make no tracks. Neutrons bear no electric charge, and hence they do not ionize the molecules of the air or any gas as they go through, for ionization is effected only by electrical forces which can tear electrons out of their places in molecules. Not making ions, they afford no footholds whereby the water-vapor can condense and mark their passage. The expansion-chamber is frustrated; and worse yet, so are the electrical devices which serve for detecting charged particles like fast protons or fast electrons, since they, too, depend on the ions which these can make. The neutron indeed might slip through all of our apparatus completely undetected, were it not liable to make collisions with nuclei so sharp and sudden

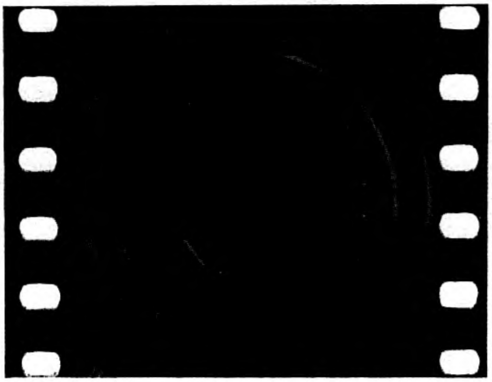


Fig. 9—Track of a proton recoiling from the impact of a neutron. (I. Curie and F. Joliot, Institut du Radium; *Journal de Physique.*)

that they might be compared with impacts of one billiard-ball upon another. Comparisons with billiard-balls are rife in physics, but seldom with so much justification. When neutrons are streaming through a gas, such impacts are suffered by nuclei of occasional atoms of the gas; and like a struck billiard-ball they recoil, and in recoiling they are able to make ions and the ions then serve to reveal them.

The track of such a recoiling nucleus, made visible in a cloud-chamber, is seen in Fig. 9. This was taken soon after the discovery of the neutron, and at a time when these particles had as yet been released only by using natural radioactive substances to project alpha-particles against various targets. Such ways of producing free neutrons are not very efficient, and accordingly one sees in the whole expansion-chamber one track and one only (though I must interpolate that according to our present knowledge, many thousands of neutrons must have traversed this chamber without happening to strike any nucleus). See now the contrast with the present time, as illustrated by Fig. 10 which shows an expansion-chamber traversed by the

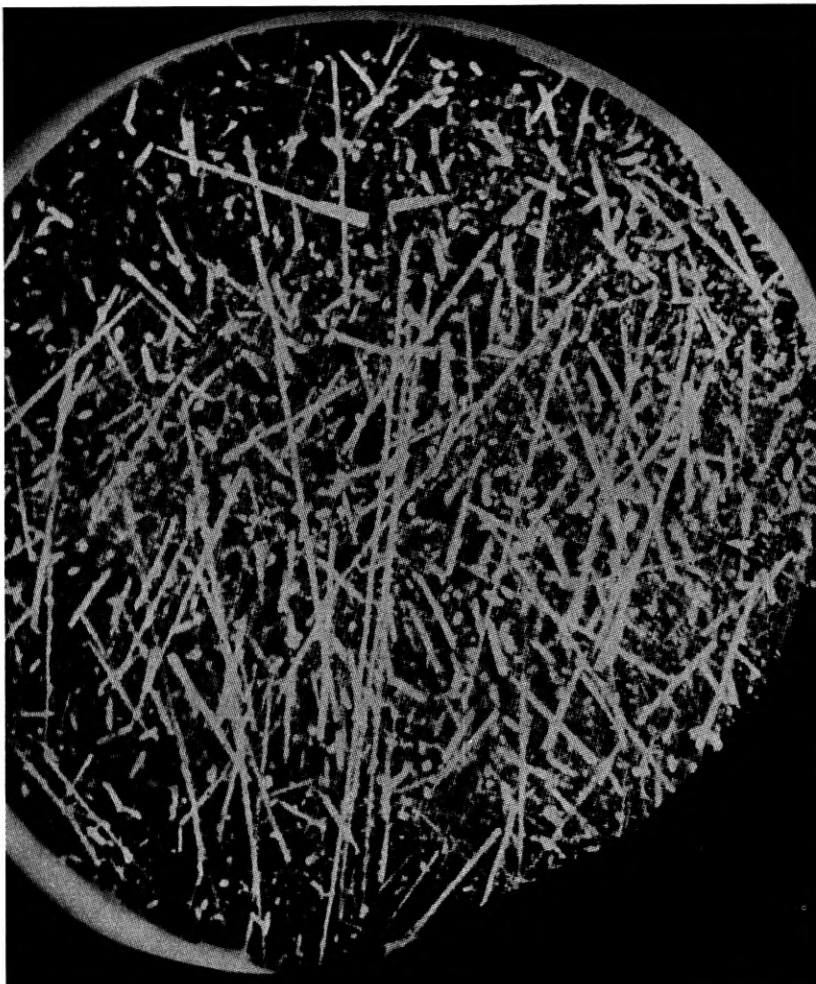


Fig. 10—Tracks of protons recoiling from impacts of a dense stream of neutrons. (F. N. D. Kurie, University of California.)

neutrons released when deuterons from a high-voltage machine bombard a target.[7] The machine in question was the famous cyclotron of E. O. Lawrence; there is no more striking illustration of the powers

[7] This was another reaction than the one just mentioned, the target being of beryllium.

which this instrument has conferred upon the scientific world, over and above those which radium has already granted.

Our digression now ends, and we return to the artificial radioactive substances, being now equipped with knowledge as to how these—or rather, many of them—can be made. As I said earlier, many radioactive isotopes differ from existing stable isotopes only in possessing an extra neutron in the nucleus; and this extra neutron can be supplied to the stable nucleus, combining it and converting it into the radioactive type. I have just exhibited one way in which the extra neutron may be, and often is, supplied. In the first-mentioned of the deuteron-deuteron reactions, a neutron is taken away from one of the deuterons by the other, which latter is thus converted from H^2 into H^3. There are many stable isotopes, of many elements, which are able to take away neutrons from impinging deuterons in this manner; a recent list gives no fewer than fifty. The resulting nucleus-types are not in every case radioactive; several are stable, including H^3 itself (at least, no one has yet discovered evidence that H^3 is unstable, though there are doubts about it). Most however *are* radioactive. The reactions in question are known as (d, p) reactions, in allusion to the fact that deuterons enter the target and protons spring out. One might imagine that the deuteron consists of a proton leading along a neutron, which it pushes into the nucleus which it strikes, itself continuing its career as a free particle.

Neutrons, however, do not have to be escorted into nuclei by protons; those which are already free, such as the ones which are released in the second of the D–D reactions, are quite well able to creep in themselves and make themselves permanently at home. My use of the verb "creep" is not entirely fanciful, for the slower the neutrons are moving as they approach a target, the better their chance of entering its nuclei. Those fresh from their origin in reactions of transmutation are usually moving much too rapidly to be able to come to a halt in a nucleus—or to be liable to capture, whichever way of putting it one may prefer. It is necessary to interpose, between the source and the target, a block of paraffin or a can of water several inches thick. If the source consists of a natural radioactive substance bombarding another element with alpha-particles and thus releasing free neutrons, the two may be mixed with each other and enclosed in a capsule which is then embedded in the centre of a paraffin sphere or immersed in water. As the neutrons make their way out, they collide again and again with the nuclei of atoms in the paraffin or the water, and these recoil from the impacts. It is not, however, their recoiling which is now of importance, but the fact that at every such impact the neutron loses some of its energy. The point about choosing water or paraffin is that they are rich in hydrogen and consequently full of protons, and the elastic impacts of the neutrons against these entail a greater average loss of neutron-energy per collision than do impacts against any other nuclei.[8] There is good reason to believe that most of the emerging neutrons have energies no greater than those which the atoms of the water or the paraffin possess by virtue of their thermal agitation. These are the neutrons which are most effective in converting stable into radioactive nuclei by letting themselves be captured.

Even yet I have not mentioned all of the ways in which radioactive substances can be and are being made. Time does not suffice for commenting on the others, but some are exhibited in Fig. 11, which

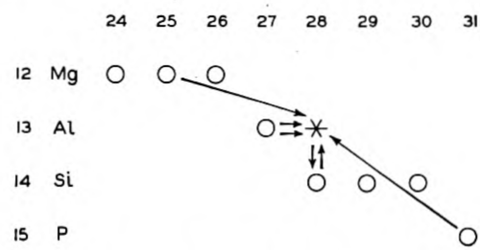


Fig. 11—Various ways of making the radioactive nucleus Al^{28}.

displays all of the stable but only one of the unstable isotopes of the four elements numbered 12 to 15. This one radioactive type, which I have tried to make more conspicuous by leaving out the rest, is the isotope 28 of aluminium—one of the few elements, which, very conveniently for physicists, has one stable isotope only. The arrows converging onto the star show the different ways in which Al^{28} is made. The two coming from the left signify that it is made by adding a neutron to the stable isotope Al^{27}; there are two of them, because the Al^{27} nucleus can either absorb a slow free neutron or annex the neutron from an impinging deuteron, whichever it has the opportunity of doing. The arrow slanting downward from the left signifies that Al^{28} can be made by bombarding magnesium with alpha-particles; some of these are absorbed by nuclei of the isotope Mg^{25} which thereupon at once emit protons. The arrow slanting upward from the right signifies a process in which phosphorus is bombarded by neutrons (fast ones, in this case!) and some are absorbed by the nuclei P^{31}

[8] Energy-transfer between an initially-moving and an initially-stationary elastic sphere is greatest when the latter is of the same mass as the former, and for protons and neutrons this equality of mass is realized within 0.1 per cent.

which thereupon eject an alpha-particle apiece. The arrow pointing straight up signifies a process in which silicon is bombarded by neutrons; some are absorbed by nuclei Si^{28}, which instantly throw out protons. With no fewer than five ways of making a single radioactive type at his command, the physicist is in a position of power which seems all the more remarkable when one recalls that as lately as five years ago he had not (knowingly) made any radioactive substance by any way whatever.

Consider now the arrow pointing away from the solitary star in Fig. 11, and the arrows pointing away from the many stars in Figs. 2 and 3. These signify what is really meant by calling an isotope "radioactive." *A radioactive nucleus is one which spontaneously changes itself into a nucleus of another element by emitting a charged particle.* (Usually it lasts an appreciable time before it does so, and this delay is to be mentioned in a complete definition of the word "radioactive.") The arrows pointing away from the stars will serve to specify these changes. All in these figures are vertical; every one of these unstable isotopes transforms itself by emitting a particle of which the mass is very small (compared to the mass-unit which we are using) while the charge is $+ e$ or $- e$, according as the transformation is to the element preceding or to the element following. These particles are positive and negative electrons. All of the man-made unstable nuclei are radioactive after this fashion, being electron-emitters; and so are more than half of those which are found in Nature.

What decides whether it shall be a positive or a negative electron which a given nucleus-type emits? Physicists cannot explain this as yet, in any adequate sense of the verb "to explain"; but we can readily see the law which governs the choice by examining the pictures. In Figs. 2 and 3 it will be seen that from each star the arrow points in whichever sense—upward or downward—it finds a circle to point at. Becoming completely animistic for the moment, I may say that the unstable nucleus wants to be stable—knows that one of its two neighbors, of identical mass-number but greater or lesser charge, is stable—knows *which* of the two is stable—and deliberately proceeds to identify itself with its stable neighbor by emitting an electron of the necessary sign. Putting the situation more drily: each of these unstable nucleus-types tends to transform itself into its adjacent stable isobar. Here "isobar" is a technical term for "nucleus of the same mass-number," and "adjacent" is a short way of saying "belonging to the preceding or the following element."

Suppose the star has circles both above and below it, *i.e.* that both of the adjacent isobars are stable (and prove themselves so by existing in Nature): how will the unstable nucleus resolve its dilemma? Such cases are rare, but not entirely absent. An example appears in Fig. 12. The elements palladium and cadmium have isobaric isotopes of mass-number 106, in spite of the fact that their atomic numbers (46 and 48) are not consecutive; silver, with atomic number 47, lies between. There is no stable silver isotope 106, but a radioactive one can be and has been created, and for this the dilemma is posed. It handles the

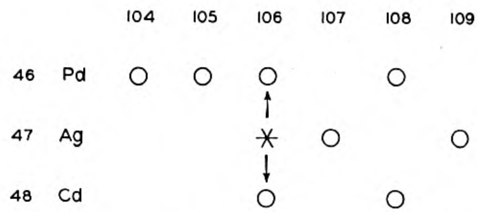


Fig. 12—Illustrating an example of isomers.

dilemma by grasping both horns! electrons of *both* signs come out of the radioactive silver. I must say that there is something which indicates that the nuclei which make one choice may be slightly different (in mass, for instance) from those which make the other. It may therefore be well to speak of silver as having two isotopes of the same mass-number 106, and a word has already been coined: they are called "isomers" of one another. This does not alter the fact that where alternative choices exist, both are elected.

On Fig. 2 we notice an arrow which points to a vacancy. No stable nucleus Be^8 is known, though there has been a very diligent search for it conducted by many ways in many places. Practically no doubt exists that Be^8 bursts of itself into two pieces (two alpha-particles) almost as soon as it is made. We thus have here an unstable (radioactive) nucleus—Li^8—which does *not* find stability by ejecting an electron, but instead hastens onward to a completer ruin. In the lower reaches of the Table of the Elements there are so many stable isotopes that the unstable ones can almost always turn themselves by one electron-emission into one or another of these, and such catastrophes are rare. Among the natural radioactive substances in the upper reaches of the Table they are common, as I now show in returning to natural radioactivity for the close of this talk.

Notice again Fig. 4, in which the stars are so many and the circles so few. If arrows were to be inserted to show the transformations, they would crisscross into a maze. I have therefore separated the figure into three: all of the circles, stars and rosettes in it will be found in Fig. 13 (which is really a pair of figures, as the caption says) and Fig. 14.

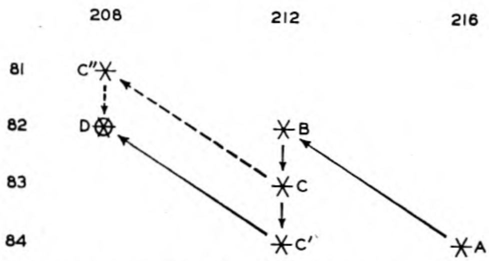


Fig. 13—Part of the thorium series of radioactive nuclei. To obtain the actinium series, imagine each star and rosette transposed one unit to the left.

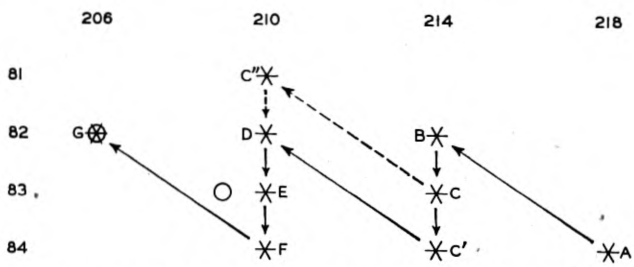


Fig. 14—Part of the radium series of radioactive nuclei.

Taking Fig. 13 as it stands, we see five of the stars and one rosette of Fig. 4 connected by arrows; each star marks a nucleus which transforms itself by emission of a particle into the one next following along the arrow-chain. The rosette stands for a stable nucleus, and would be replaced by a circle were it not distinguished by being the terminus of such a chain. These five radioactive isotopes and one terminal nucleus-type belong to the "thorium series," and are known as thorium A, thorium B, thorium C′ and so on, according to the letters which adjoin their stars. This is an unlucky bit of terminology, for it suggests that all are isotopes of the same element, which is clearly far from the truth.

Taking Fig. 13 again and imagining each star moved by one unit to the left (so that *e.g.* the star A goes to 217), we now are thinking of five more stars and another rosette of Fig. 4, duly connected by arrows. These constitute (a part of) the "actinium series" and are known as actinium A, actinium B and so forth.

Taking Fig. 14 as it stands, we find ourselves confronted by eight more of the stars and the last rosette of Fig. 4, connected by arrows. These constitute a part of the "radium series" and are known as radium A, radium B and so on. The "so on" covers more than it did in the other two cases, this chain continuing to the terminus here marked as radium G, though usually known by a different name.

Surveying the scene of these *massive* radioactive nuclei, one is struck by the fact that not all of the arrows are vertical. Many are slanting, and by their slant and their length they show that they represent the emission of alpha-particles. It is a feature of some (not of all) of the unstable nuclei of mass-numbers greater than 200, that they strive toward stability by emitting these. For this feature we should be very grateful, since it was by the use of alpha-particles from natural radioactive bodies that Rutherford achieved the first of transmutations; though physicists now can transmute without their aid, no one can guess how long they would have waited without trying had they not had that encouragement. Vertical arrows also are seen, but again there is a contrast to the lighter isotopes; all of the electrons emitted by radioactive nuclei of mass-numbers beyond 200, or by natural radioactive isotopes of whatever mass, are negative. But for the fact that positive electrons had been observed among the cosmic rays in 1932, they would have been discovered along with the first examples of artificial radioactive isotopes in 1934, and what a sensation that would have been!

More than by anything else, probably, one is impressed by the concatenation of these radioactive nuclei. A long journey to stability lies ahead of thorium A and actinium A, a longer one still ahead of radium A; but the total lengths of the journeys are greater yet, for they begin farther back. In Fig. 15 we behold the three series of radioactive isotopes in their entirety, and it is seen that the three "A-products," as they are called, are midway in the evolution and not at its beginning. The manner of drawing of this figure is changed from the preceding, atomic number being laid off along the horizontal axis and mass-number along the vertical; also, crosses and circles and dots are used to mark the members of the actinium, radium and thorium series respectively, and have no bearing on stability or instability. The actinium series should lie lower than it is drawn, with its terminus AcD lying midway between ThD and RaG; the mistake is incurred so as to diminish the overlappings which would otherwise confuse the picture.

Except for a few created in the last three years by transmutation, every known nucleus-type of mass-number greater than 209 and atomic number greater than 83 (as well as a few of slightly lower values) is found in Fig. 15. It appears that 83 and 209 are critical values of nuclear charge and mass, beyond which the constituents of nuclei—neutrons and protons, presumably, and whatever others there may be—cannot unite into stable systems.[9] All of these nuclei beyond 209 which are found in Nature are seeking for stability by the emission of particles, but never finding it until they have emitted

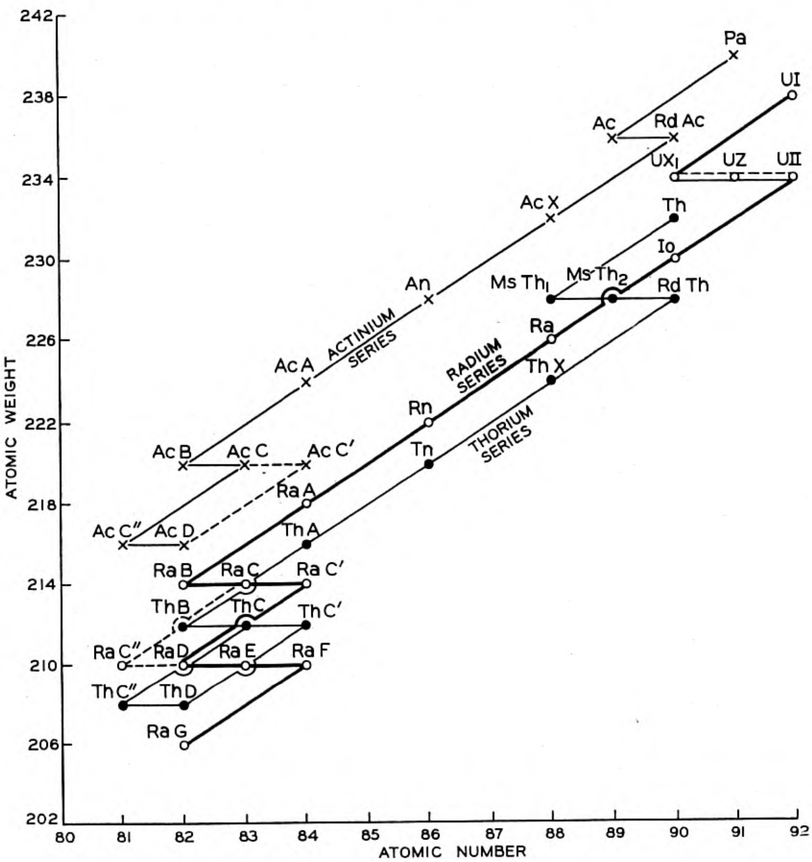


Fig. 15—The three series of radioactive substances.

sufficiently many to convert themselves (or rather, the residues of themselves) into one or another of the three isotopes of element 82—*lead*—which are marked by rosettes in Fig. 4. For an obvious reason these three are called thorium lead, actinium lead and radium lead. "Ordinary" lead as it comes from most mines is a mixture of many isotopes, but the lead which is found in close association with thorium or with uranium proves its origin from vanished atoms of these metals

[9] I recall from an earlier footnote that some of these very heavy nuclei (notably thorium 232 and uranium 238) are so very long-lasting that "unstable," while strictly correct, seems much too strong a word for them.

by being preponderantly the isotope 208 or the isotope 206 as the case may be.

I pause to mention, in justice to Rutherford, that it was he who proved by study of some of these natural radioactive bodies that each is transforming itself into a different element; also it was his associate Soddy who by similar studies was led to distinguish the first-to-be-recognized isotopes, that is, different radioactive forms of one and the same element. The way for making such diagrams as Figs. 2 and 3 and 4 was prepared before 1914 by these two men, though some of the facts embodied in Fig. 4 were not then available because of want of knowledge of atomic numbers, and all of the knowledge embodied in Figs. 2 and 3 was non-existent because no radioactive isotopes of these elements had yet been created and nobody knew as yet how to distinguish their stable isotopes. Also it should be mentioned that only the extraordinary potency of radioactive substances in affecting our instruments of measure enables the physicist or the chemist to recognize the element to which a radioactive isotope belongs, nay even to detect its presence. With radium and a few others, it has been possible to amass enough of the substance to see and to weigh; with the great majority of natural and with the totality of artificial radioactive isotopes, nothing of the sort has even been approached, and we should still be unacquainted [10] with them if they had been stable.

Three examples of transmutation which occur in these upper ranges of the Periodic Table deserve to be recorded in even so brief a report.

In Fig. 14, notice the circle in row 83 and column 209 which (as I earlier said) represents the highest stable nucleus—bismuth 209. Radium E, represented by the star to its right, is clearly bismuth 210; by the testimony of its mass-number and atomic number, it differs from stable bismuth nuclei by the possession of an extra neutron. If bismuth should be bombarded by neutrons, either free or bound into deuterons, would it be transformed into radium E? Livingood at Berkeley did bombard ordinary bismuth with very energetic deuterons, and did succeed in producing a radioactive substance which agreed with radium E not only in emitting negative electrons, but also in converting itself into a substance emitting alpha-particles, and the agreement extended to details of the emission. No doubt exists that he was making radium E out of bismuth 209 by enabling deuterons to transfer their constituent neutrons to this latter, just as H^3 is made from H^2 in the first of the deuteron-deuteron reactions.

[10] This statement should be qualified slightly, for some of the artificial radioactive nuclei spring from reactions of transmutation which are so well understood that the observer could justifiably infer the existence of the nuclei in question even if he did not observe them.

In Fig. 15, notice that all of the members of the thorium series have mass-numbers divisible by 4, or equal to $4n$ with various integer values given to n. This is accordingly called the "$4n$ series," and one readily sees what is meant by calling the radium and the actinium series by the names of "$4n + 2$" and "$4n + 3$" series respectively. One begins at once to wonder whether there is not a "$4n + 1$" series. Such a series was long sought after in vain, and no member of it has yet been discovered in Nature; but in the laboratory of the Curies in Paris thorium has lately been strongly bombarded by neutrons, and a new sequence of radioactive bodies has thus been engendered which has already been followed through several steps, and is in all probability the series so long missing.

As to the remaining feat—the creation of elements beyond uranium—it is now beyond doubt. Fermi and his school at Rome, Hahn and Meitner in Berlin, Curie and Joliot in Paris have all borne witness to it. In one way it seems the most romantic of all the feats of transmutation, for Nature had apparently set 92 as the limit of nuclear charge, and now man has transgressed it. The process is begun by exposing uranium to bombardment by streams of neutrons. It appears that when a uranium nucleus has captured a neutron, it finds itself not strongly enough charged to hold together, and proceeds to emit one negative electron after another in its search for stability. Each emission transfers the nucleus to an element one step higher, without affecting its mass-number; and the authorities agree that there are at least four consecutive emissions, after the last of which the atomic number is 96! This addition of four new elements to the Periodic Table opens a new field to chemists, one which they can scarcely have expected ever to be able to enter. The four have no proper names as yet, a curious circumstance in view of the fact that discoverers of new elements have thus far been in great haste (sometimes too great haste) to name them. Mendeleieff long ago used to denote an expected but undiscovered element by prefixing "eka" to the name of the element just above the vacant place in the Periodic Table; these new four are sometimes called eka-rhenium, eka-osmium, eka-iridium and eka-platinum, but on looking at such words one is inclined to prefer the atomic numbers.

Now to summarize. The world as we knew it before the days of transmutation was constructed out of some two hundred and fifty kinds of atoms, each consisting of a nucleus surrounded by a family of electrons. Of these 250 kinds of nuclei the great majority were stable and perpetual, but some forty were unstable—doomed to perish in due time, by ejecting either alpha-particles or negative electrons.

These were the natural radioactive bodies. To these forty kinds of radioactive nuclei already found in Nature, physicists have added in a scant four years no fewer than two hundred and twenty more by the art of transmutation. Every chemical element which is known to exist at all, with the sole exception of hydrogen, has at least one radioactive type of nucleus or isotope, and many have more than one. These man-made radioactive nuclei are often made simply by adding neutrons to nuclei which already exist and are stable. There are, however, other and more complicated processes, in which neutrons or protons or deuterons or alpha-particles impinge on nuclei and seem to enter them, and other particles leap out. Many radioactive bodies have already been made in two or three different ways, some in as many as five.

Few things are riskier than to suggest a limitation either on the scope of Nature or on the possibilities of science, and many a scientist is remembered chiefly for such a suggestion which later the course of events proved foolish. Yet there are circumstances in this case which give some ground for suspecting that already we may know nearly all of the stable and may have created nearly all of the radioactive nucleus-types. Several hundreds of types have now been made by the art of transmutation, but of them nearly all which seem to be stable are not new, and nearly all which are new are radioactive. This implies that the earth has already been stocked with almost all the stable nucleus-varieties, but not necessarily that we have yet come near to making all of the possible radioactive kinds. There are however reasons for believing that most of the remaining types have so little durability, that even if they were to be made they would not last long enough to be identified as radioactive. Nature probably has come quite close to building all the imperishable forms, we possibly almost as close to creating all of those which are capable of a little but not a perpetual life. Perhaps it is fitting that people who are not immortal should not be able to construct new elements which are immortal; but we at least can rejoice in having diversified the scene of the world with a surprising number of new substances which are none the less remarkable for being transitory.

Abstracts of Technical Articles from Bell System Sources

Protection Features for the Joint Use of Wood Poles.[1] J. O'R. COLEMAN and A. H. SCHIRMER. The paper reviews the historical development of joint use and the general results to date of studies of protective problems of lower and higher voltage joint use. The safety features are reviewed from the standpoint of (1) subscribers' premises, (2) employees, and (3) telephone plant. Characteristics of equipment of power and telephone plant as far as they relate to this problem are given. The various factors which determine magnitude and duration of the current and voltage in the telephone plant resulting from a contact with power conductors are discussed. Improved methods for obtaining safety under various conditions, where higher voltage joint use is found to be the best over-all solution, are described.

High-Speed Motion Picture Photography Applied to Design of Telephone Apparatus.[2] W. HERRIOTT. High-speed motion pictures are employed at Bell Telephone Laboratories as a visual aid in the study of problems associated with the design, manufacture, and testing of telephone apparatus. A new high-speed camera of the optical compensator type operating at 4000 pictures per second is described, and its application to the study of problems associated with telephone apparatus is discussed.

Mass Ratio of the Carbon Isotopes from the Spectrum of CN.[3] F. A. JENKINS and DEAN E. WOOLDRIDGE. With a source containing carbon enriched about ten times in C^{13}, the violet CN bands have been photographed with a dispersion of 0.63A/mm. Measurements are given of the lines of low rotational quantum number in the 0,0, 0,1 and 0,2 bands of $C^{13}N^{14}$, as well as of $C^{12}N^{14}$. The vibrational constants of the normal states of both molecules are accurately determined, and give a value of the isotope mass coefficient $\rho = \omega_e^i/\omega_e$ of 0.97898 ± 0.00002, corresponding to a mass for C^{13} of 13.0088. This is in essential agreement with the mass-spectrograph value, and it is shown that the finer corrections to the isotope effect are negligible in this case.

[1] *Elec. Engg.*, March 1938.
[2] *Jour. S. M. P. E.*, January 1938.
[3] *Phys. Rev.*, January 15, 1938.

Composition and Structure of Hevea Latex.[4] A. R. KEMP. Data and present views relating to the composition and structure of the latex particles are presented. The number of particles in one gram of 40 per cent latex was calculated to be 7.4×10^{12} on the basis that they have an average particle mass of 0.054×10^{-12} gram (from the microscopic data of F. F. Lucas, page 146).

A study was made of the effect of several factors on the water content of rubber in pressed coagulum from fresh and treated latices. The average value for the water of retention of rubber coagula from fresh latex was found to be about 11 per cent, increasing to about 22 per cent in the case of old latex and deproteinized rubber from alkali-treated latex. This water appears to be held mechanically in the colloid hydrocarbon structure of the latex particles.

The particle structure of sheet rubber is discussed and it is suggested that plasticization by milling involves the conversion of the gel hydrocarbon shell on the rubber particles to sol rubber through oxidation.

Ultraviolet Microscopy of Hevea Rubber Latex.[5] FRANCIS F. LUCAS. Samples of bulk rubber latex received in sealed cans from two sources have been investigated by means of the ultraviolet microscope. The advantages of the ultraviolet microscope are (*a*) an enormous increase in resolving power, (*b*) selective absorption of the ultraviolet light by many substances, and (*c*) the ability to section optically very small objects suited to the purpose.

Brief descriptions of the apparatus and technic are given. Artifacts have been minimized in the preparation of the slides. A multitude of particles bordering on colloidal dimensions have been clearly resolved. Particle size measurements, including complete tabular data and a particle size distribution curve for each specimen, are given. Approximately 90 per cent of the particles are 0.50 micron or less in diameter. The shape of the latex particle appears predominantly spherical, although elongated particles and irregular shaped particles are found. Optical sections in some cases show these to be groups of particles; two particles may coalesce to form one. Many of the smaller particles appear to lose their electrical charges and become attached to larger particles. Possible effects of ultraviolet radiation are discussed.

Dielectric Losses in Polar Liquids and Solids.[6] S. O. MORGAN. Dielectric loss is the energy dissipated as heat in a dielectric when it is in an electric field. Losses due to dipoles represent only one of a num-

[4] *Indus. and Engg. Chem.*, February 1938.
[5] *Indus. and Engg. Chem.*, February 1938.
[6] *Indus. and Engg. Chem.*, March 1938.

ber of possible means by which energy may be dissipated in a dielectric; there may be losses due to free ions and also due to dielectric polarizations other than dipole polarizations. However, in many materials dipoles are an important source of loss; it is the purpose of this paper to consider some of the typical cases of dipole loss and to point out some of the relations between chemical composition and dipole loss which follow from the recent experimental and theoretical study of dielectric behavior.

Order-Disorder Transformations in Alloys.[7] FOSTER C. NIX and WILLIAM SHOCKLEY. An extensive résumé of a subject which is becoming of increasing interest to physicists and metallurgists. The article divides into two parts, forty pages being devoted to the theories of the order-disorder phenomenon, and twenty pages to experimental studies of superstructures.

Thyratrons for Grid-Controlled Rectifier Service.[8] G. H. ROCKWOOD. It is common knowledge that the output voltage of a rectifier fluctuates with changes in load current and supply line voltage. Frequently these fluctuations are so large that means must be used to correct them. This is particularly true when the rectifier feeds a load having a high back electromotive force and a small resistance, such as a storage battery. The facility with which the output voltage may be controlled by the use of thyratrons as the rectifying element has encouraged the design of tubes especially suited to this purpose. There is available a variety of circuits such that the output voltage of a rectifier may be made to obey any desired law. The successful application of these circuits depends upon the degree of reliability of the thyratron tubes used in them. To be most successful the tubes must possess certain characteristics. This paper gives a brief review of the operation of grid-controlled rectifier circuits, discusses the requirements which such circuits impose on the tube characteristics, and describes a particular type of thyratron with mercury-plus-argon filling which has proved especially useful in such rectifiers.

Progress in Non-ferrous Metals and Alloys During the Past Few Years.[9] EARLE E. SCHUMACHER and ALEXANDER G. SOUDEN. The purpose of this review is to present the more important advances in the non-ferrous field during the past few years, the topics discussed being classified broadly as fundamental and practical. The former

[7] *Reviews of Modern Physics*, January 1938.
[8] *Trans. the Electrochemical Society*, Vol. LXXII, 1937, pp. 213–224.
[9] *Mining and Metallurgy—Institute of Metals Division*, January 1938.

includes those studies that have done most toward developing the basic science of metals and alloys, and the latter includes technical developments and applications.

Theory of Order for the Copper Gold Alloy System.[10] W. SHOCKLEY. The theory of order and disorder, in the form used by Bragg and Williams, is extended to arbitrary composition of the constituent elements. The work is based upon the nearest neighbor interaction assumption of Bethe and the connection between the Bethe and Bragg-Williams theory is shown. In order to extend the Bragg-Williams theory to compositions other than 25 and 50 atomic per cent, new definitions of order are developed. The results are presented in terms of phase diagrams and curves showing energy vs. temperature, specific heat vs. temperature and state order vs. temperature. These results are of importance in giving a general picture of the order-disorder transformation for a wide composition range. They are not in detailed accord with experiment due to the rather idealized picture underlying the nearest neighbor assumption.

A Theory of Noise for Electron Multipliers.[11] W. SHOCKLEY and J. R. PIERCE. The noise in secondary-emission electron multipliers is considered from a theoretical viewpoint. The noise properties of a stage are correlated with its secondary-emission properties: the mean value m and mean-square deviation δ^2 of the number of secondaries per primary. If $\overline{I_{p\Delta f}^2}$ and $\overline{I_{s\Delta f}^2}$ denote the mean-square noise current lying in the frequency band Δf in the primary- and secondary-electron currents, then $\overline{I_{s\Delta f}^2} = m^2\,\overline{I_{p\Delta f}^2} + \delta^2 2e\overline{I_{p\Delta f}}$ where $\bar{I}_p$ is primary direct current. This result is applied to many-stage multipliers. For n similar stages $\overline{I_{s\Delta f}^2} = \overline{M^2 I^2_{p\Delta f^2}} + \delta^2[M(M-1)/m(m-1)]2e\overline{I_{p\Delta f}}$ where $M = m^n$ is the over-all gain of the multiplier.

Wave Guides for Electrical Transmission.[12] G. C. SOUTHWORTH. The transmission of electric power at extremely high frequencies through rods or "wires" of dielectric and through metal tubes, without the usual return conductor, was predicted mathematically many years ago. Recently experiments have confirmed this theory. Wave guides offer the possibility of transmitting very wide frequency bands and consequently extremely large numbers of speech channels without the high attenuations encountered in radio; in fact, constantly decreasing attenuation with increasing frequency is predicted for one type of wave.

[10] *Jour. Chemical Physics*, March 1938.
[11] *Proc. I. R. E.*, March 1938.
[12] *Elec. Engg.*, March 1938.

Some of the properties of the waves and the apparatus used in studying them are described in this article.

Recent Development in Hill and Dale Recorders.[13] L. VIETH and C. F. WIEBUSCH. A new sound-on-disk recorder has been developed in which is used the principle of feeding part of the output of the system back to the input of the associated driving amplifier in properly controlled relationship. The use of this principle, which is widely used in feedback amplifiers, replaces the usual practice of providing dissipative elements for the control of an electrically driven vibrating system. Heretofore no practical application of feedback to electromechanical systems has been made, possibly because the requirements for stable operation of such systems are difficult of achievement. Through recent developments these requirements have been satisfactorily met. The new recorder is capable of recording on wax or direct-recording material without appreciable effect upon its characteristics, which include uniform response from 30 to 12,000 cps. and exceptional freedom from distortion. The recorder is extremely simple and affords easy means for field calibration from the feedback element, whose output is in direct proportion to the stylus velocity. These means also make available a monitoring voltage which, properly amplified, gives a precise aural picture of the stylus behavior during recording.

Internal Friction in Solids—III. Experimental Demonstration of Thermoelastic Internal Friction.[14] C. ZENER, W. OTIS and R. NUCKOLLS. In order to demonstrate the presence of thermoelastic internal friction, the authors measured the internal friction of a copper reed over a wide frequency range (50 to 4000 cycles/sec.). They obtained a maximum precisely at the predicted frequency. The observed variation of internal friction with frequency proves that, over a wide frequency range, the internal friction due to the flow of heat back and forth across a reed is of a larger order of magnitude than that due to all other causes. Independent experiments of Bennewitz and Rötger on wires of silver, aluminum, brass, steel, and glass are shown to furnish an equally striking demonstration of thermoelastic internal friction.

[13] *Jour. S. M. P. E.*, January 1938.
[14] *Phys. Rev.*, January 1, 1938.

Contributors to this Issue

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