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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.

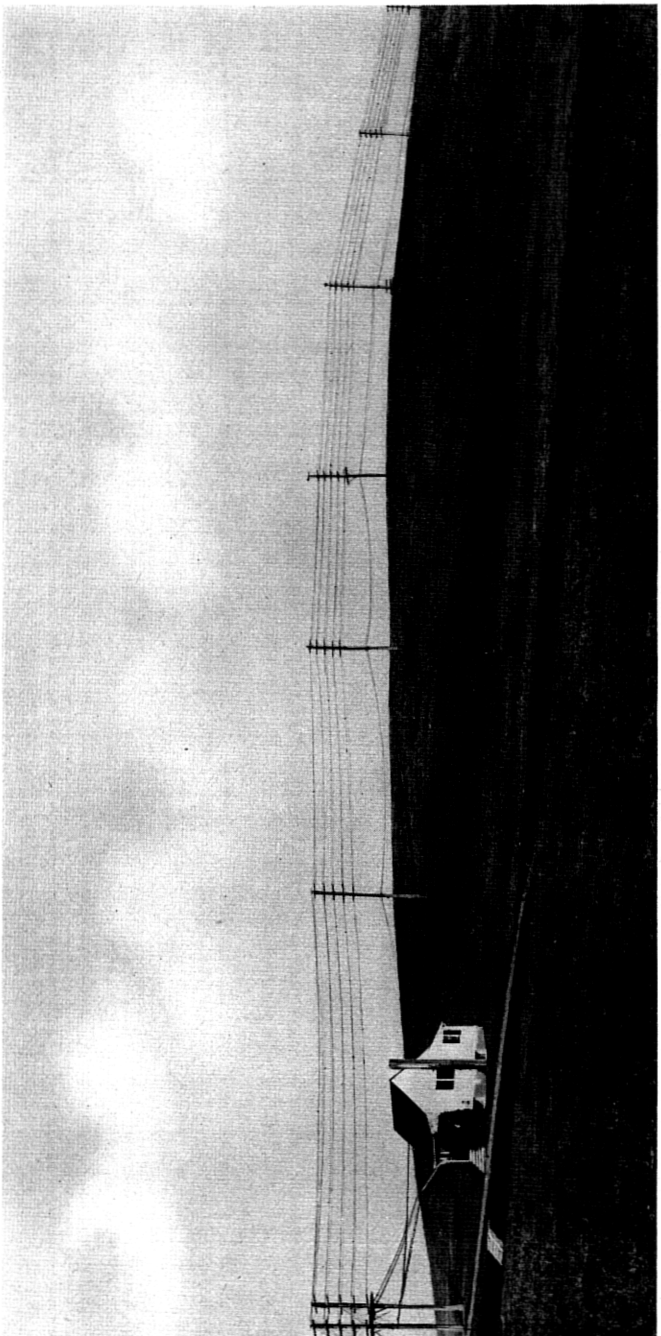

Fig. 1—Line 1 and test house at Chester, New Jersey.

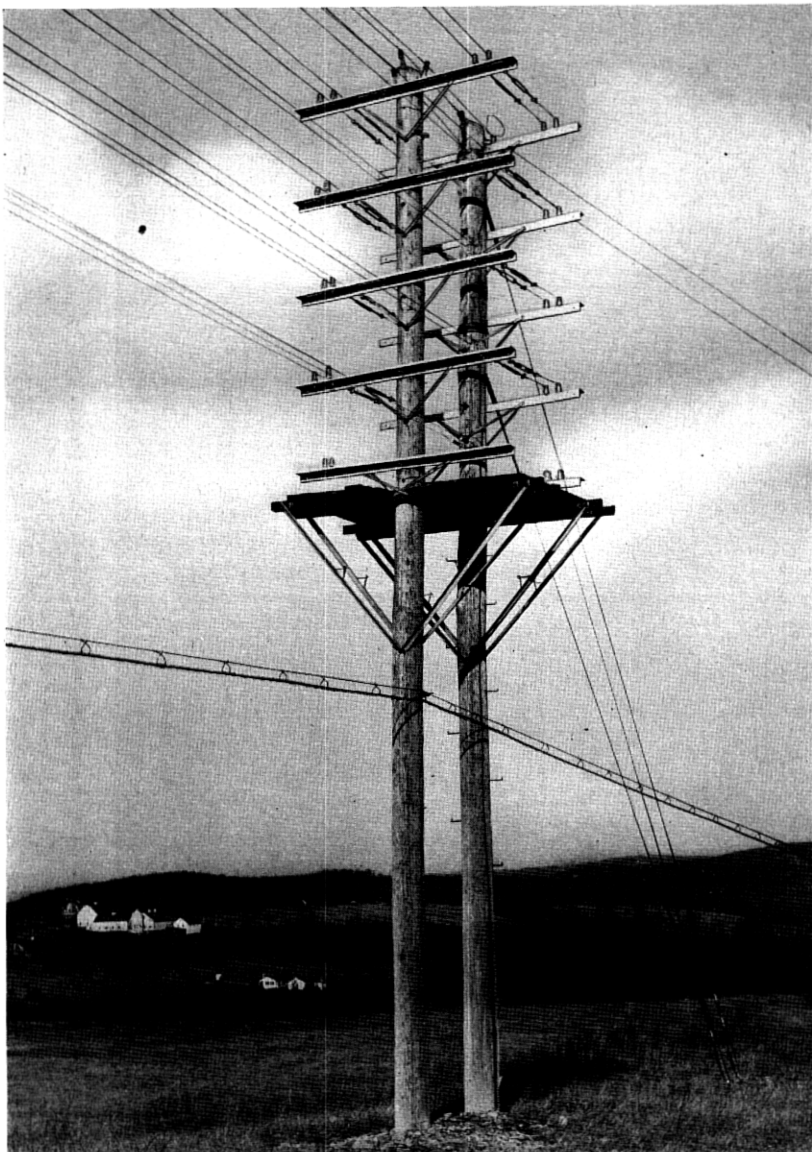

Fig. 2—Double pole construction at end of Line 1.

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 repre-

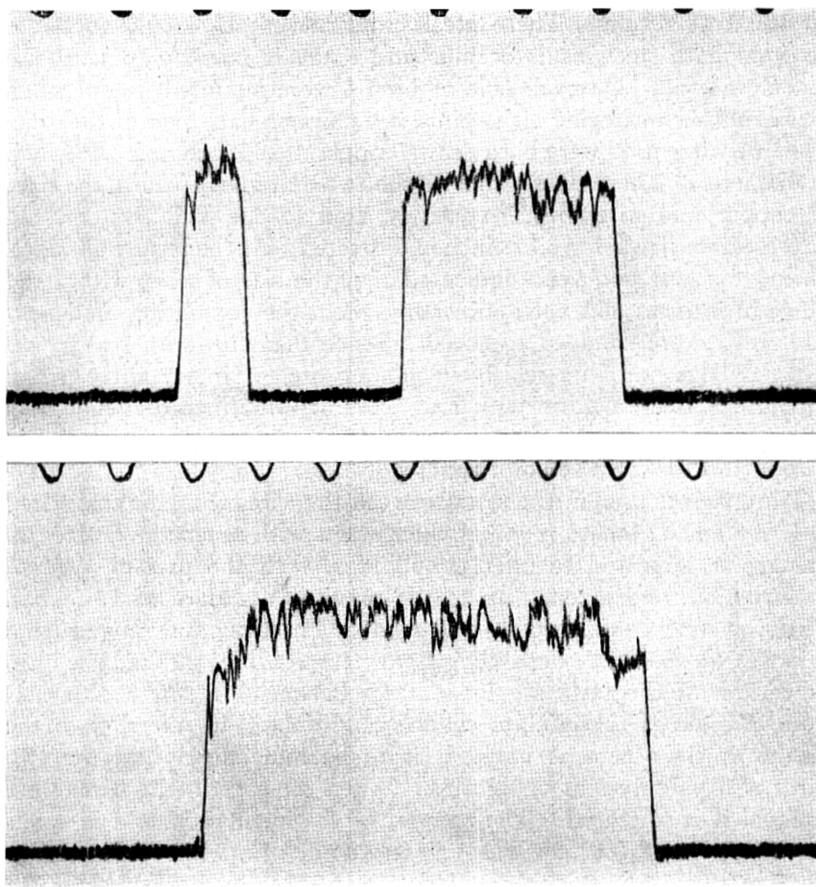

Fig. 3—Oscillograms of swinging wire contacts.

sentative 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.

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.

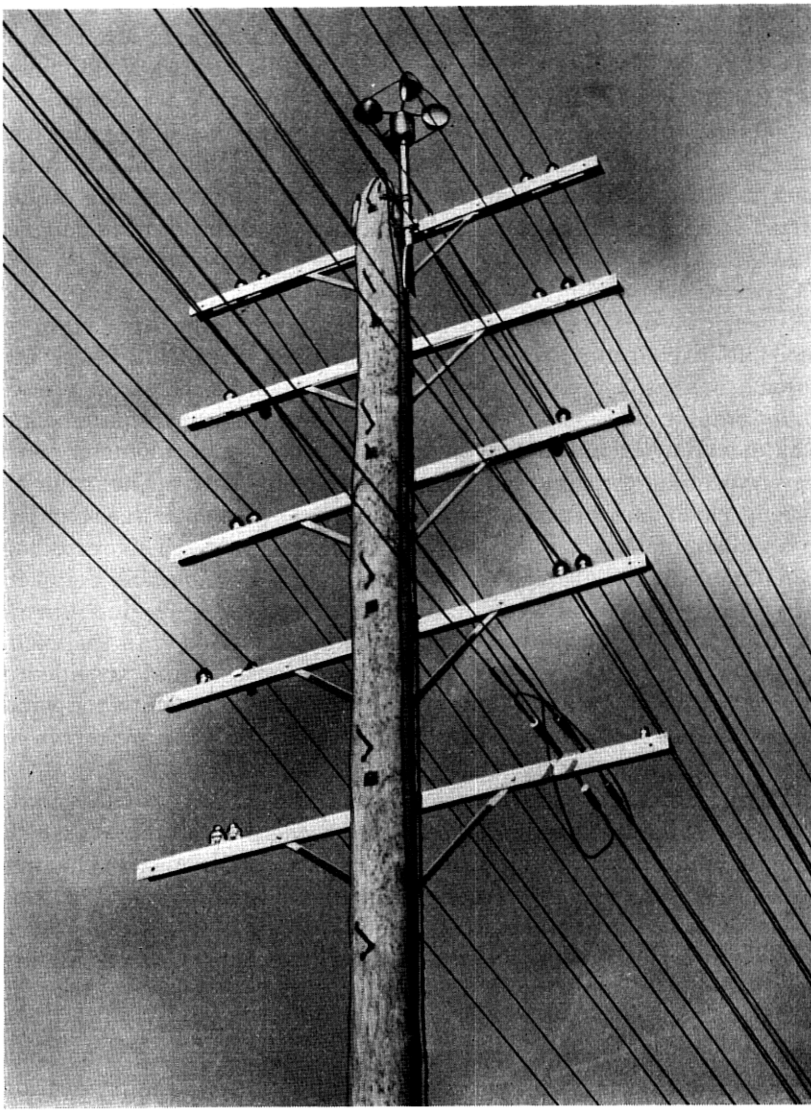

Fig. 4—Cup anemometer mounted on pole of Line 1.

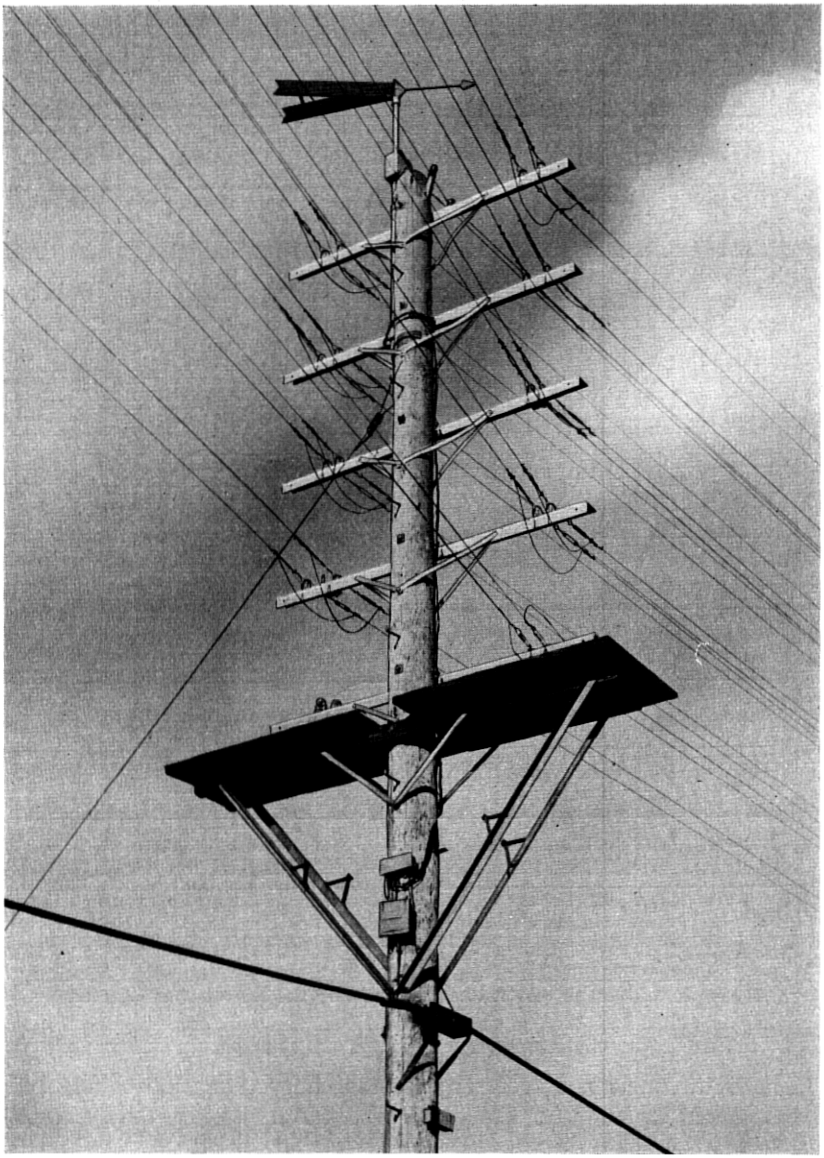

Fig. 5—Wind vane mounted on pole of Line 1.

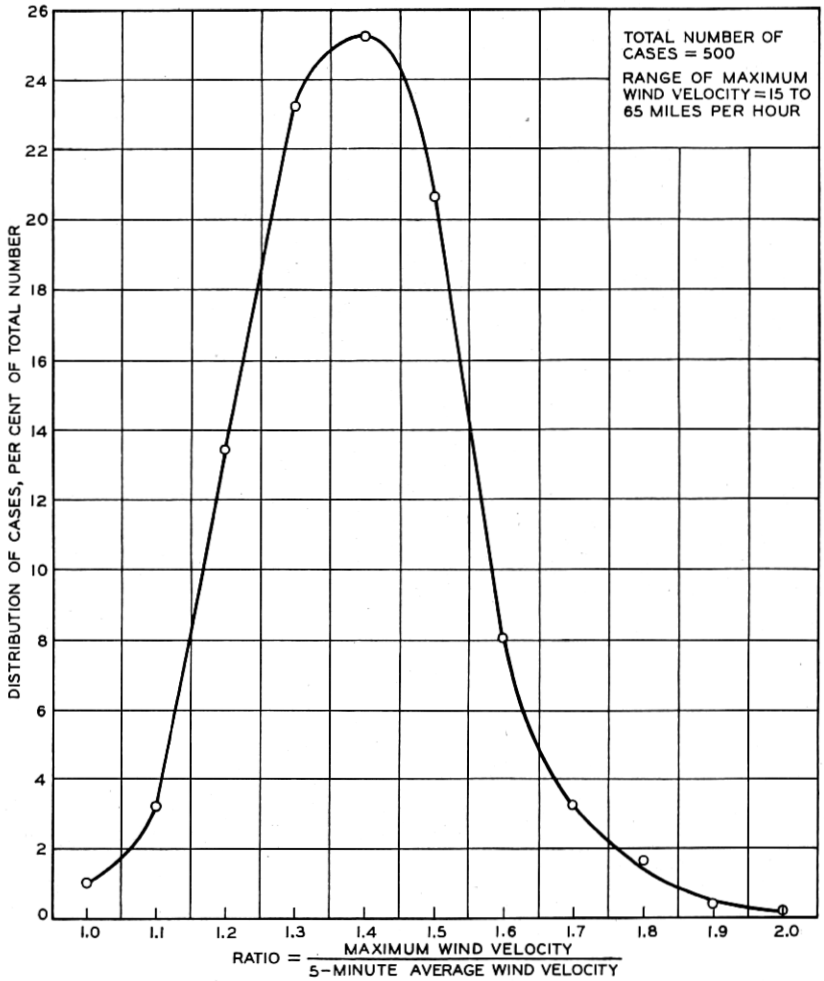

Fig. 6—Frequency distribution of the ratios of maximum instantaneous velocities to five-minute average velocities as recorded by the Burton anemometer.

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.

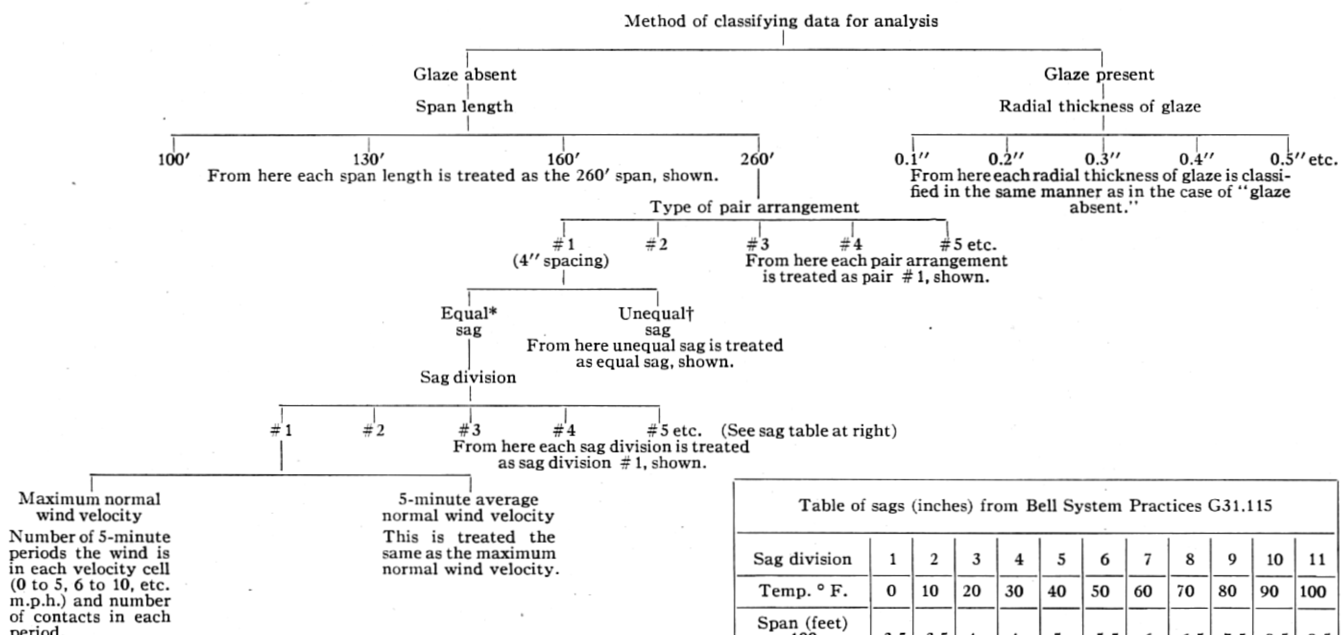

Table of sags (inches) from Bell System Practices G31.115

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.

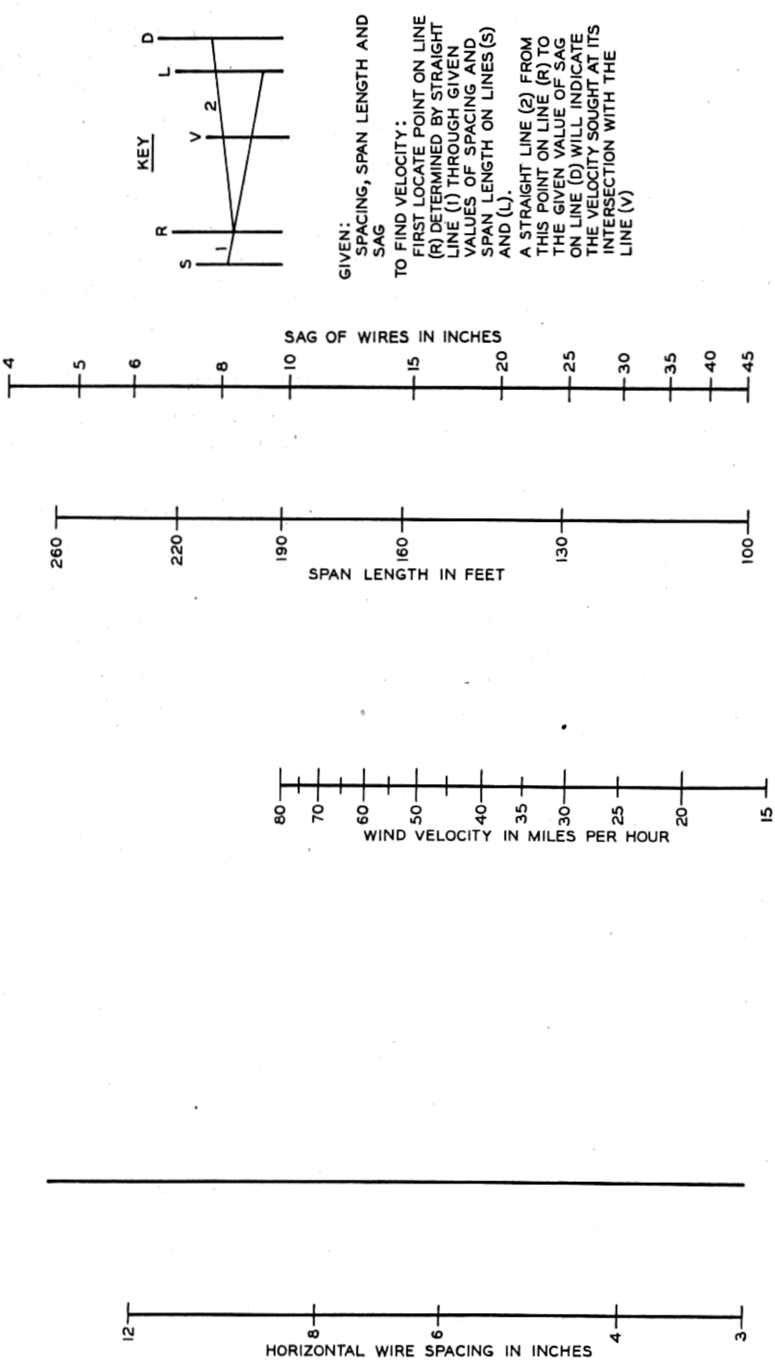

Fig. 8—Nomogram for determining wind velocity (threshold) normal to the line at which wires of a pair begin to contact.

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

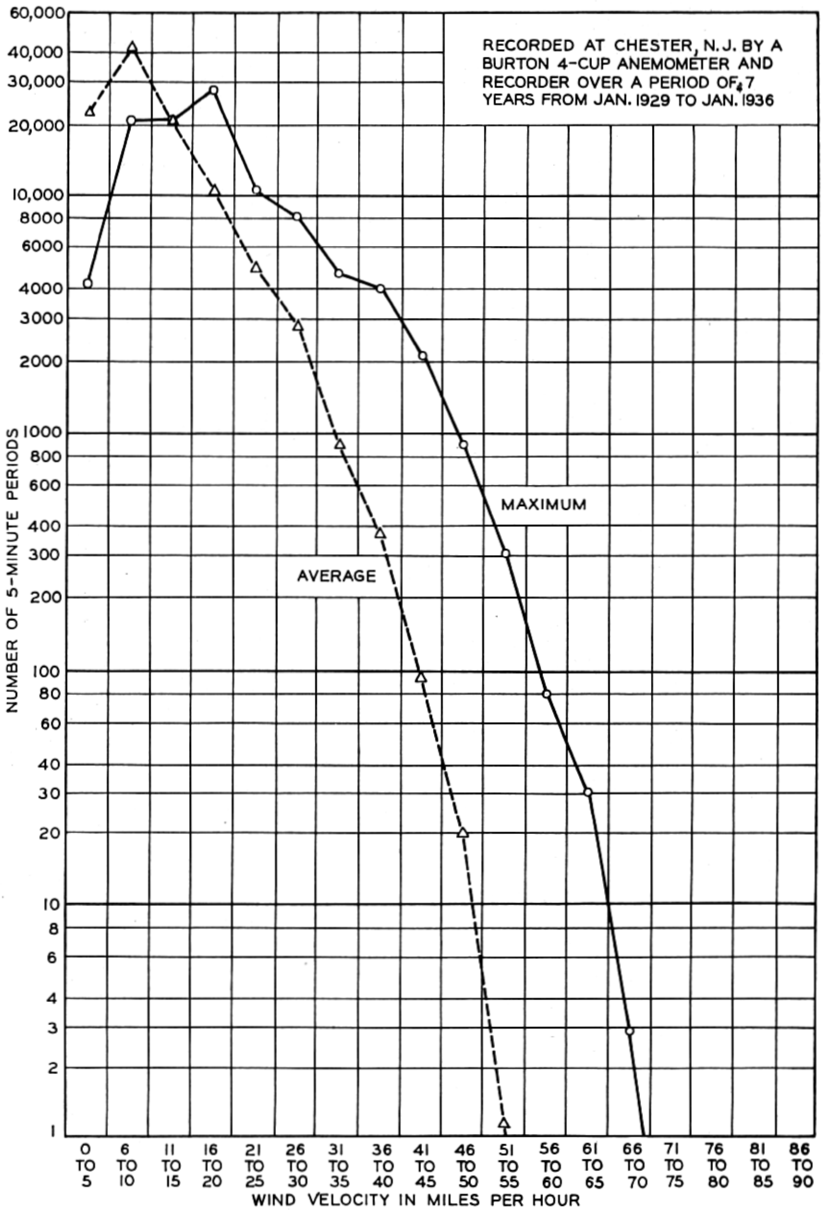

Fig. 9—Distribution of the annual maximum and five-minute average wind velocities.

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

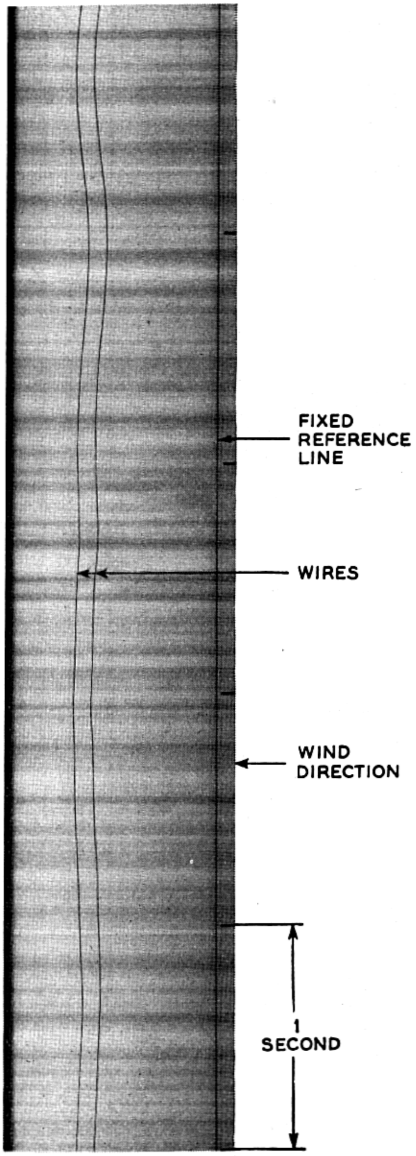

Fig. 10—A photograph of a section of motion picture film showing the transverse movement of wires in wind.

TABLE II

Deflections of Wires in Winds

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
Values of α' Computed from Measurements Made on Motion Picture Films—Degrees	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

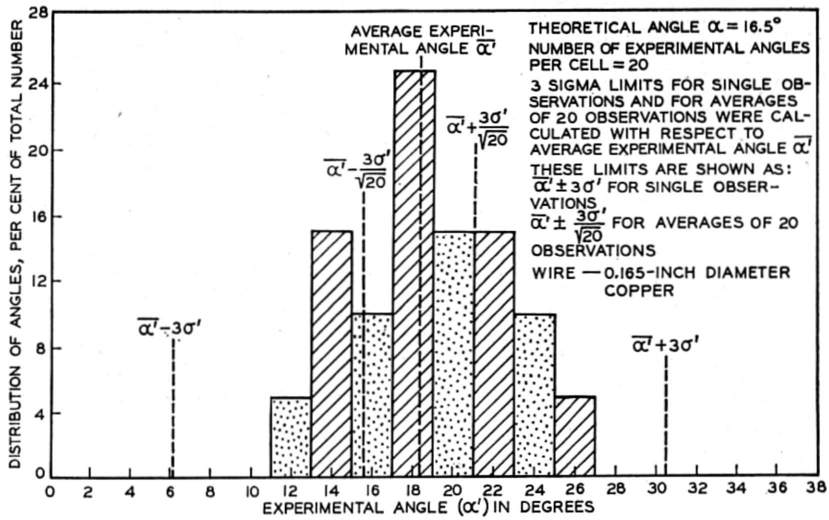

Fig. 11—Distribution of experimental angles of deflection of a suspended wire in a transverse wind velocity cell of 25.1 to 27.0 miles per hour.

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.

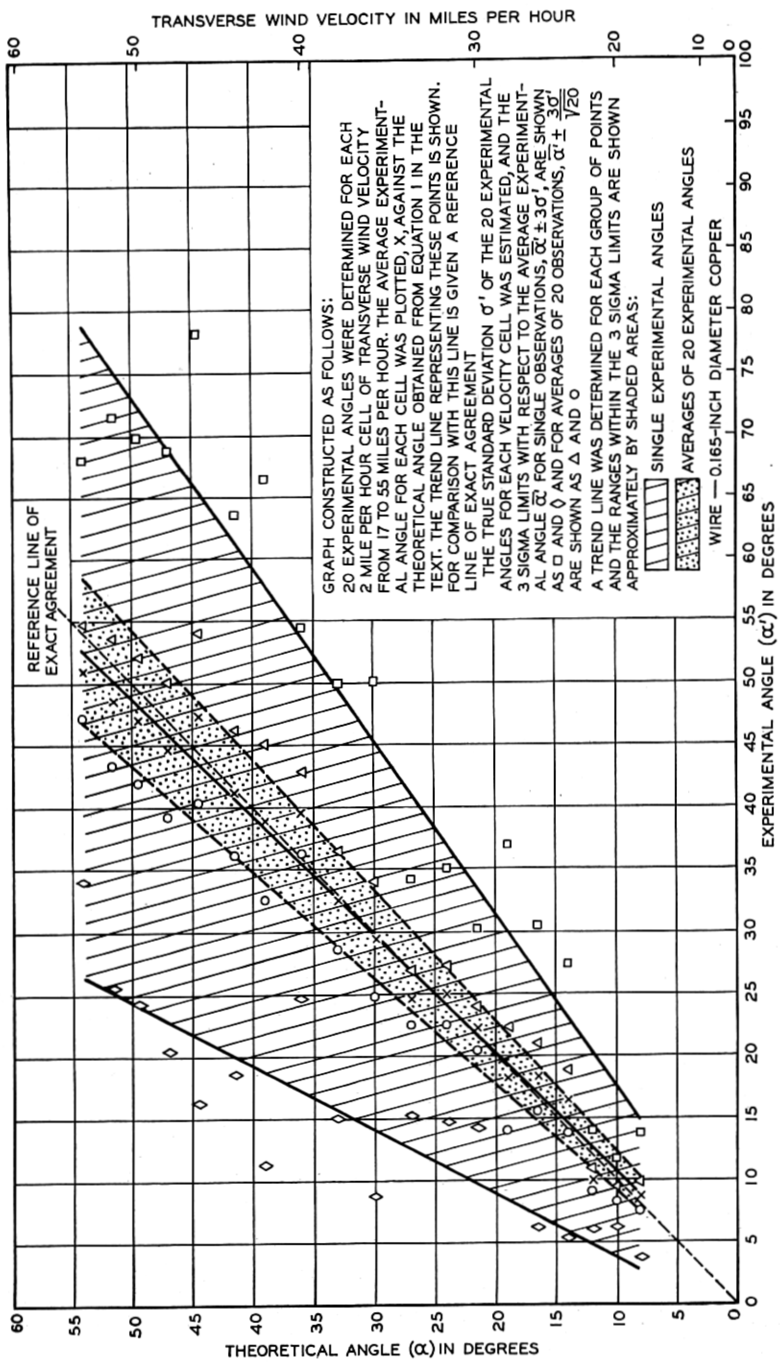

Fig. 12—A comparison of experimental and theoretical angles of deflection of a suspended wire in winds.

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.

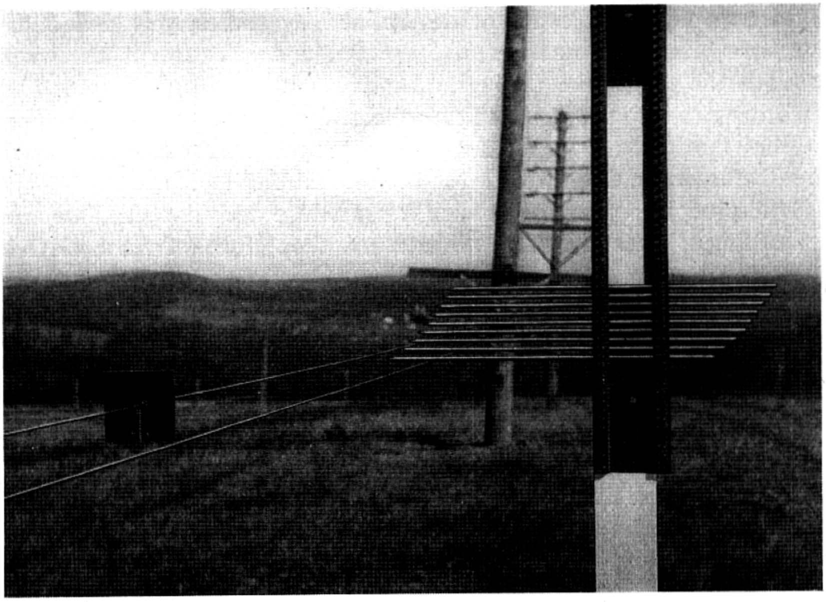

Fig. 13—Apparatus for the accelerated test.

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

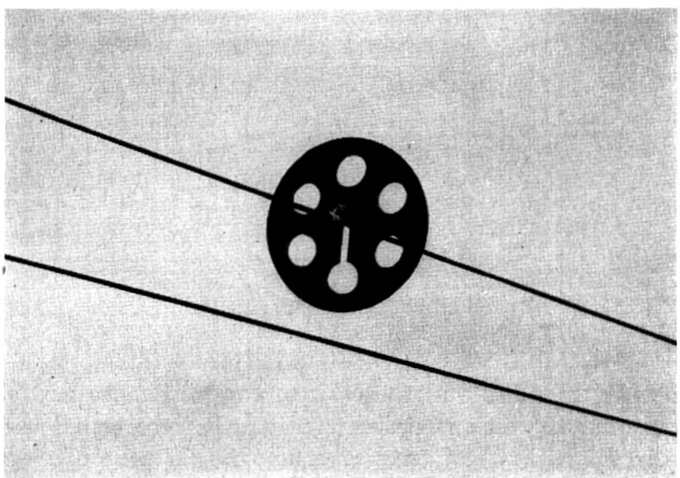

Fig. 14—Insulating disc.

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.

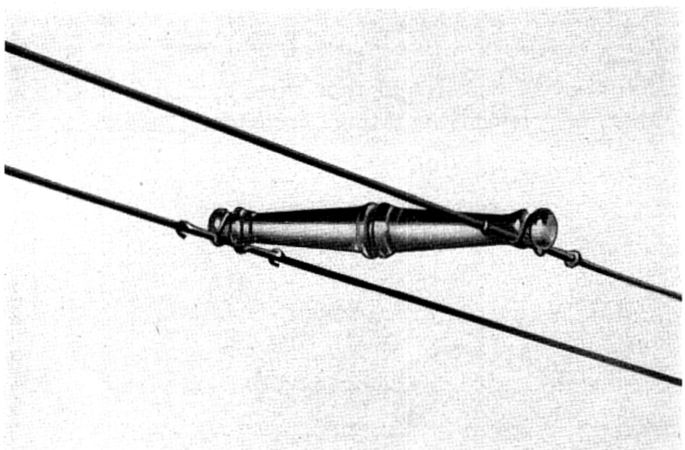

Fig. 15—Insulating spacer.

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_s = 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:

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

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.