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-

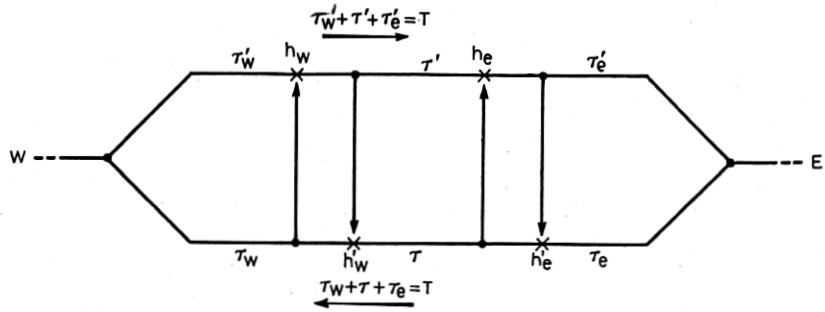

Fig. 1—Schematic of generalized four-wire circuit equipped with two echo suppressors.

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.

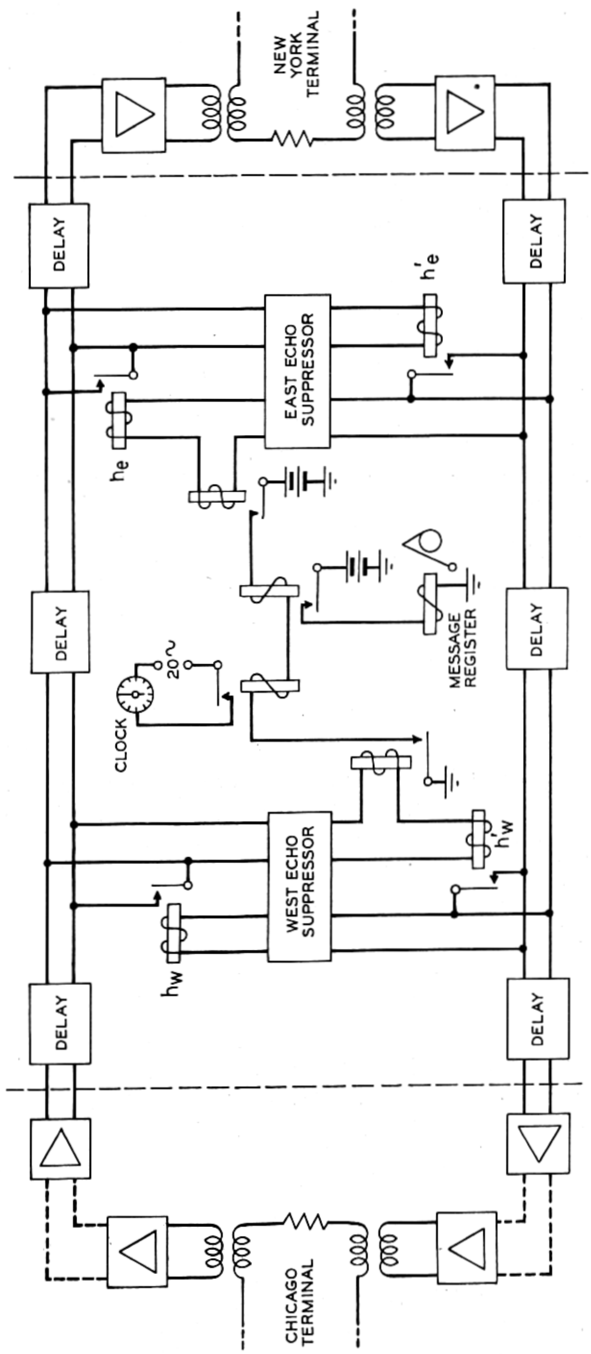

Fig. 2—Circuit arrangement used for experimental results.

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 ± 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	0.043	0.186	0.073	0.146	0.023
	0.139	0.043	0.200	0.073	0.146	0.023
1*b*	0.193	0.043	0.186	0.100	0.200	0.050
	0.193	0.043	0.200	0.100	0.200	0.050
1*c*	0.293	0.043	0.186	0.150	0.300	0.100
	0.293	0.043	0.200	0.150	0.300	0.100
2*a*	Same as 1*a*					
2*b*	0.139	0.043	0.186	0.073	0.200	0.023
	0.139	0.043	0.200	0.073	0.200	0.023
2*c*	0.139	0.043	0.186	0.073	0.300	0.023
	0.139	0.043	0.200	0.073	0.300	0.023
3*a*	Same as 1*c*					
3*b*	0.316	0.043	0.186	0.250		0.023
	0.316	0.043		0.250	0.146	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	0.043	0.136	0.050	0.146	0.023
	0.116	0.043	0.150	0.050	0.100	0.023
7*b*	0.116	0.043	0.136	0.050	0.210	0.023
	0.116	0.043	0.170	0.050	0.146	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,

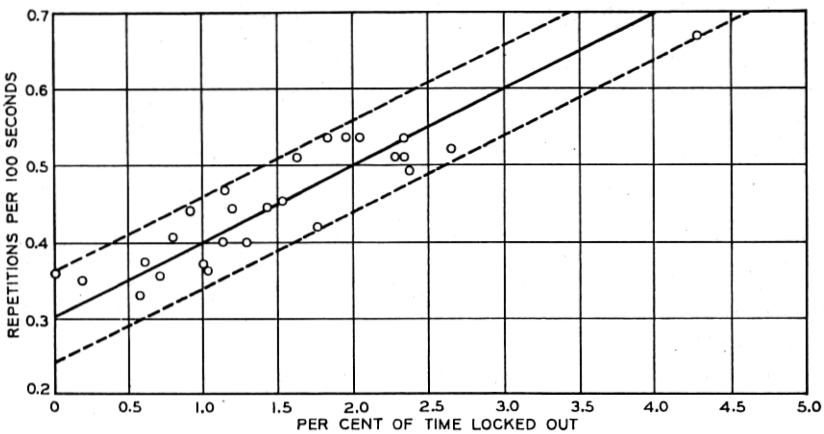

Fig. 3—Observed variation of corrected repetition rate with per cent of time locked out.

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-

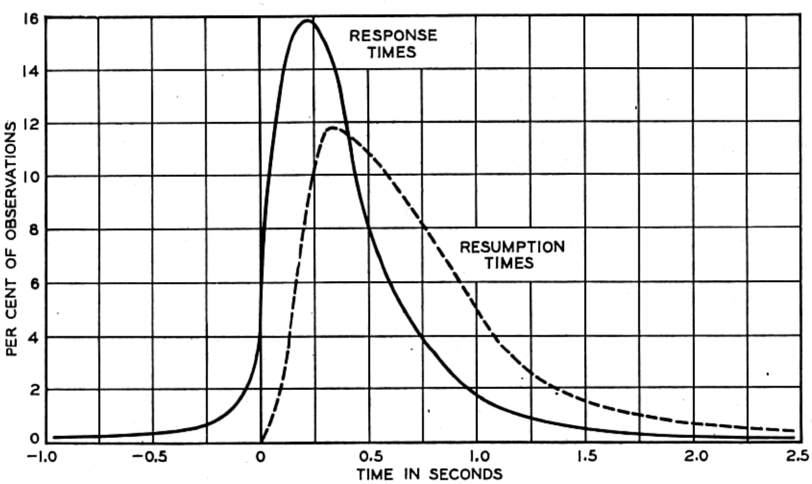

Fig. 4—Observed distribution of resumption and response times.

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

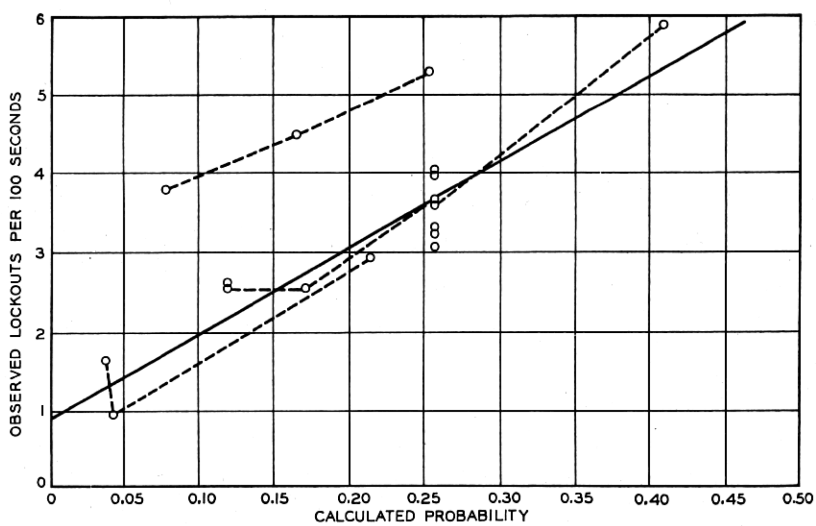

Fig. 5—Observed lasting lockouts vs. calculated probability.

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

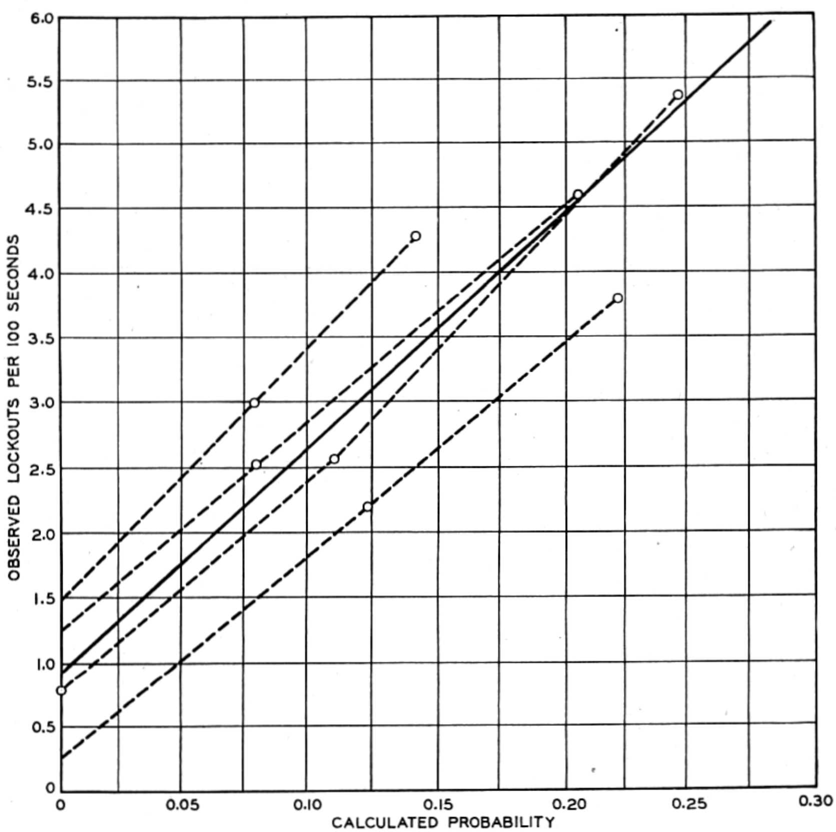

Fig. 6—Observed releasing lockouts vs. calculated probability.

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-

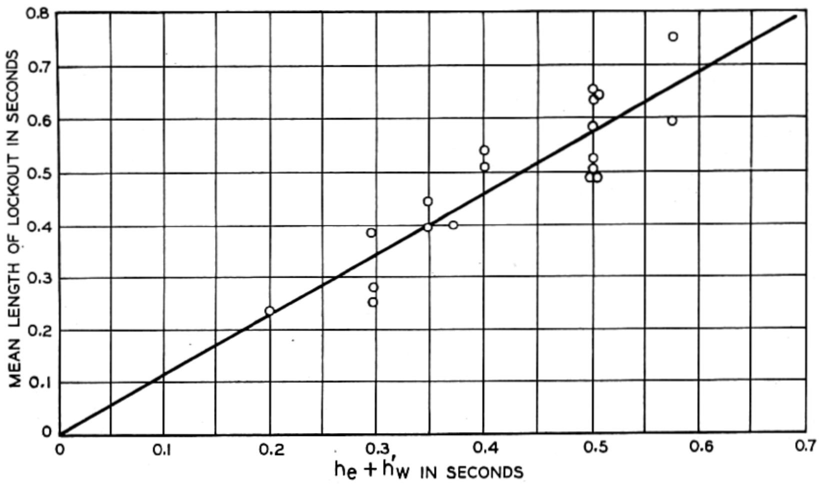

Fig. 7—Observed length of lockout as a function of relay hangovers.

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.

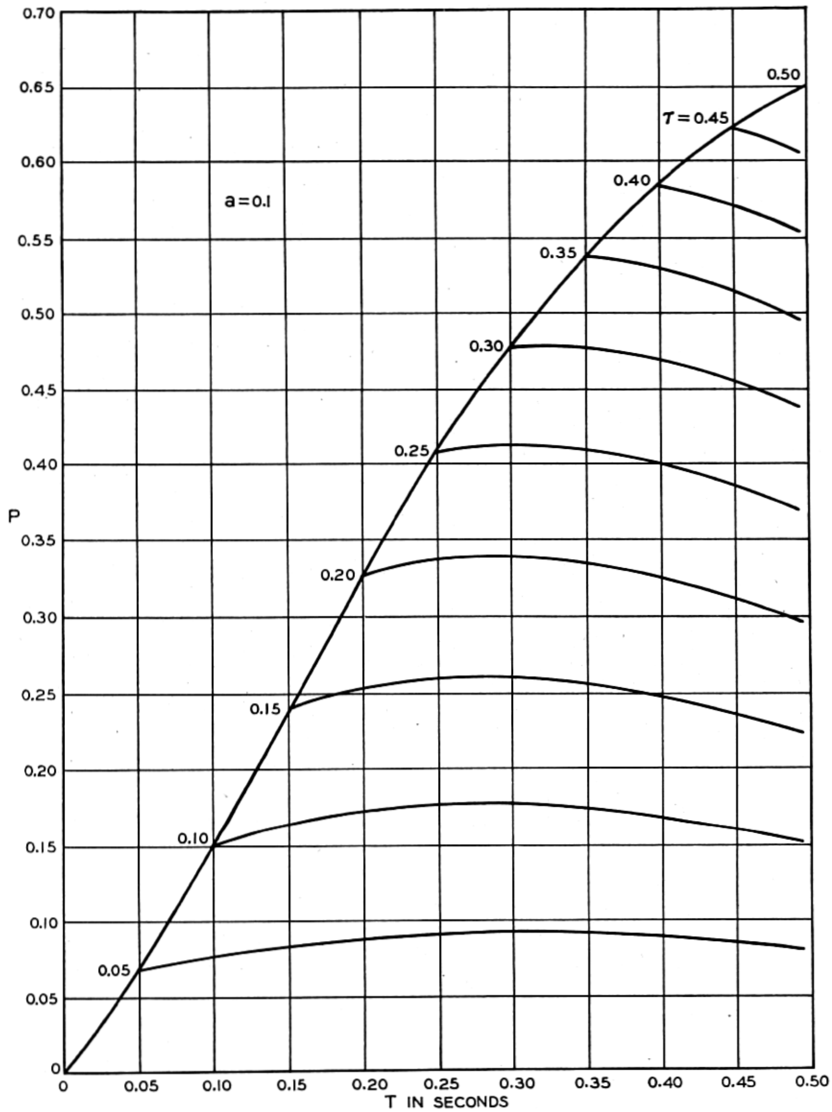

Fig. 8—Calculated probability of lockout as a function of total circuit delay.

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

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

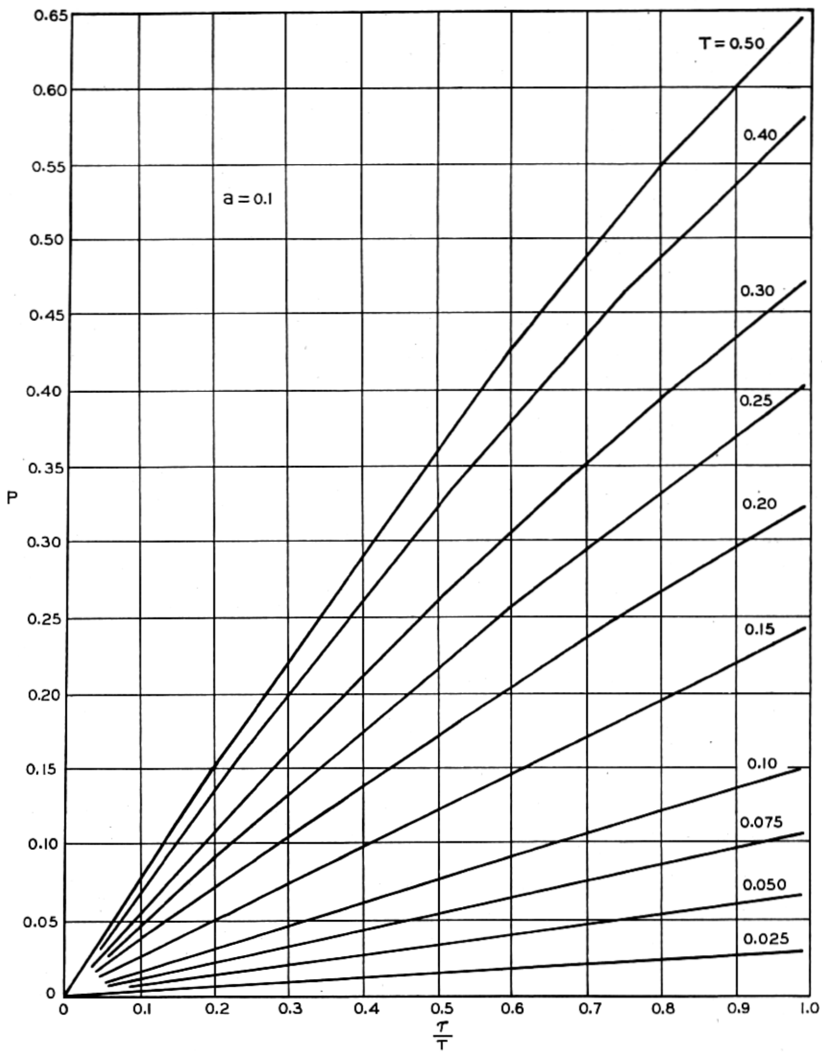

Fig. 9—Calculated probability of lockout as a function of the ratio of the delay between the suppressors to the total circuit delay.

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,

$$\begin{aligned} a &= a, \\ b &= a + T - \tau, \\ c &= a + T + \tau, \end{aligned}$$

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

$$\begin{aligned} a &= 0.100, \\ b &= 0.100 + \tau, \\ c &= 0.100 + 3\tau. \end{aligned}$$

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

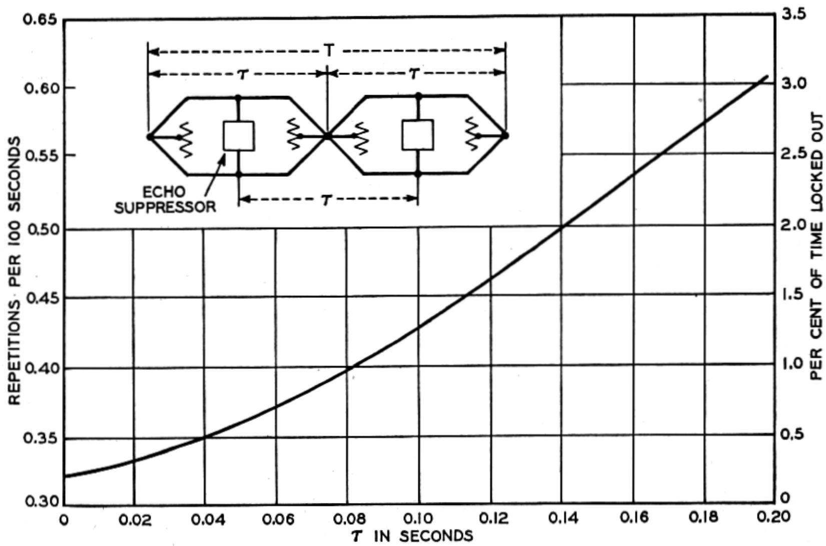

Fig. 10—Calculated per cent of time locked out, and repetition rate for the indicated circuit conditions.

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

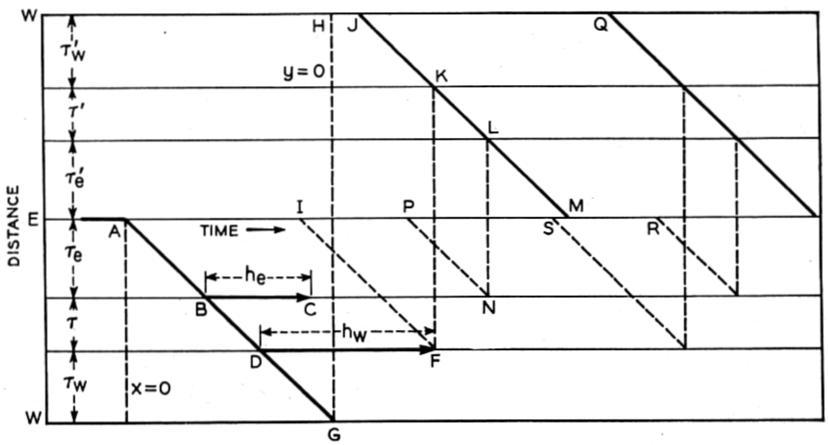

Fig. 11—Time relations in four-wire circuit for determination of limits of integration.

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

$$a = h_w - (\tau_w + \tau_w'),$$
$$b = h_w,$$
$$c = h_w + (\tau + \tau').$$

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

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

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

$$\alpha = h_e - \tau - (\tau_w + \tau_w'),$$
$$\beta = h_e.$$

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

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

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

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