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SPECIAL STUDIES IN ELECTROLYSIS MITIGATION, No. 2

ELECTROLYSIS FROM ELECTRIC RAILWAY CURRENTS AND ITS PREVENTION—AN EXPERIMENTAL TEST ON A SYSTEM OF INSULATED NEGATIVE FEEDERS IN ST. LOUIS

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1. GENERAL DISCUSSION

INTRODUCTION

In a recent paper [1] the authors have discussed briefly the relative merits of some of the more important possible methods of electrolysis mitigation, and have drawn from that discussion the conclusion that insulated negative feeders should provide an economical and effective means of reducing electrolysis troubles to a practically negligible minimum. This discussion, however, was based mainly on theoretical considerations, and there has been

[1] Electric Railway Journal, Jan. 3, 1914.

up to the present time an almost complete dearth of quantitative experimental data bearing on the practical working out of systems of this character. While it is true that insulated feeders have been used abroad for many years, they have found no application in this country until within the last few years, and no comprehensive experimental data as to their operation has been published. Moreover, the feeder systems that have been used abroad have for the most part been used in connection with boosters, and the use of insulated feeders has usually been associated with the use of boosters in the minds of most engineers in this country. It is only natural, therefore, that engineers should be reluctant to install feeder systems of this character in the absence of any experimental data showing their effectiveness for accomplishing the purposes intended. It has, therefore, been necessary, in order to get adequate experimental data bearing on these problems, to install some experimental systems expressly for the purpose, and work of this sort has already been done in a few places, with the cooperation of electric railway companies. In making these installations localities were selected where conditions may be considered as normal and fairly representative of average conditions in American cities. The systems installed have been designed in accordance with the demands of service conditions, and are, therefore, of such nature that the experimental data obtained in connection with them is of a very practical character. Additional work of this kind is contemplated, and it is hoped through these investigations to accumulate evidence which will establish beyond doubt the practical possibilities of insulated negative feeder systems as a means of taking care of electrolysis troubles.

In connection with the general investigations that have been carried out by the Bureau of Standards for the past two or three years a considerable amount of preliminary work was done during the summer of 1912 in the city of St. Louis, as well as in other places. It was found that conditions in St. Louis were not exceptional, but that, in common with many other American cities, more or less trouble from electrolysis was experienced, and the tests showed that there was need for improvement in this direction. As a result of these preliminary tests a full report was

prepared by the engineers of the Bureau of Standards and submitted to the United Railways Co., of St. Louis. In that report the conditions as to danger from electrolysis were fully set forth, and recommendations were made for removing the cause of the damage.

In making these tests the engineers of the Bureau of Standards had the active cooperation of the officials of the United Railways Co., who furnished all necessary data in regard to track layout, feeder installations, car schedules, etc., which were required in order to design in detail a suitable system for the transmission of the current and its return to the power stations in a manner to take care of the traffic adequately and at the same time eliminate in a large measure future trouble from electrolysis. Based on these data and the experimental data obtained by the Bureau of Standards a thorough study of the whole situation was made, and the conclusion was arrived at that the best way to take care of electrolysis troubles was through the installation of insulated negative feeders.

When this report was submitted to the United Railways Co. an arrangement was made with them for the actual carrying out of the recommendations in the case of one of the substations of the company for the purpose of demonstrating the effectiveness of the proposed plan. The work of installing the negative feeders was done by the United Railways Co., and throughout the entire investigation the representatives of the Bureau of Standards had the cordial cooperation of the engineers and officials of the company, and the services of several of the company's men to assist in carrying on experimental work.

PURPOSE AND PLAN OF INVESTIGATIONS

The purpose of the test was twofold—first, to demonstrate the effectiveness of the insulated return feeder system as a means of mitigating electrolysis troubles; and, second, to determine the relative cost of securing equally good electrolysis conditions by the use of insulated and uninsulated negative feeders. In order to obtain data on the relative merits of the uninsulated and insulated systems it was necessary to install a system of negative feeders complete and in such a way that they could be converted into an

insulated or uninsulated feeder system at will. Since the negative feeders of the substation selected for the test were on poles or in fiber ducts, this could readily be accomplished by tying the bus bar to the tracks near the power house for the uninsulated system and removing such ties and inserting suitable resistance taps for the insulated system.

In both cases the feeders themselves were insulated from the tracks between the point at which they were tied into the tracks and the bus bar, but since in the uninsulated system the feeders were at the same potential as the tracks at both ends, the potential drops on the feeders were, of course, the same as the potential drops on the tracks which they parallel, and hence electrical conditions were substantially the same as they would be if the feeders had been uninsulated, and the relative electrolysis conditions and costs would also be identical. In the present case the tests were first made on the uninsulated feeder system; then suitable resistance taps were placed at the power house and at certain points out on the line to give proper distribution of current between the feeders, and the tests were repeated to show the change in conditions. A complete record of both of these series of tests is given below.

The station selected for this experimental investigation was the new Ann Avenue substation, located at the corner of Mississippi and Ann avenues. The rated capacity of this station is 4000 kilowatts at the present time, and the peak load (average for one hour) was at the time the tests were made about 7540 amperes. The average load for 24 hours was 3500 amperes, giving a load factor of about 46 per cent. It will therefore be seen that conditions at this station as regards size and character of the load are fairly representative of average conditions in a moderate-sized city substation. The track network in the district fed by the station is shown in Figs. 1 and 2. These show that only one single track passes immediately by the station, and another single track passes along the street one block to the east. This is therefore an unfavorable location with respect to returning the current to the station, because the cross section of rails approaching the station is unusually small. However, this was not the governing factor in determining the location of this station. On this account a

Fig. 1.—*Original negative feeder system, Ann Avenue district*

Fig. 2.—*Insulated negative feeder system, Ann Avenue district*

relatively large amount of copper would have to be installed in any case, whether the insulated or uninsulated system be used, and therefore the cost of returning current to this station, per kilowatt of capacity, would be expected to be considerably higher than the average, and this fact makes the test of the insulated system a more severe one from the economic standpoint, although it has no appreciable bearing on the effectiveness of the system in reducing electrolysis troubles.

The station in question is a new station which was just nearing completion at the time arrangements were made for the proposed tests. A considerable amount of negative copper was already in place, and in designing the proposed insulated feeder system this copper was allowed to remain; extensions were made where necessary and the current distribution was adjusted by means of resistance taps. The cross-sectional area of the feeders is not, therefore, just as it would have been if a new insulated feeder system had been installed throughout; and this also tends to make the cost run somewhat higher than would otherwise have been the case.

The original feeder layout designed by the engineers of the United Railways Co. for the negative return is shown in Fig. 1, and the system as finally completed for the insulated feeder layout is shown in Fig. 2. An examination of these two figures shows that changes were made in three cases.

In one case a feeder of 1 000 000 circular mils cross section had been designed to run from the negative bus eastward along Ann Avenue and tied to the tracks at both Eighteenth Street and Ann Avenue and Twelfth Street and Ann Avenue. The change made here was merely to remove the tie at Eighteenth Street and Ann Avenue and install a pair of 0000 cables running directly from the tracks at Eighteenth Street and Ann Avenue to the bus bar, thus giving two separate feeders to those two points instead of one common feeder. The length of each of these 0000 feeders was about 760 feet.

A second change will be noted on Gravois Avenue. The original feeder layout contemplated running one feeder of 1 000 000 circular mils to Victor Street and Gravois Avenue, and another to Jefferson and Gravois avenues. The feeder at Jefferson and Gravois avenues was allowed to remain, but the feeder running to Victor

Street was cut loose from the tracks at this point and extended to California and Gravois avenues, a distance of about 2300 feet.

The third extension was in one of the feeders running north on Mississippi Avenue. The original plan contemplated running one 1 000 000 circular mil cable to Mississippi and Geyer avenues and a similar cable to Mississippi and Lafayette avenues. A resistance was put in series with the feeder extending to Geyer Avenue, and the Lafayette Avenue feeder was extended to Lafayette Avenue and Grattan Street, and a resistance was inserted in the tap to Mississippi and Lafayette avenues. The amount of copper added in extending the feeder from Mississippi Avenue to Grattan Street was 1300 feet of 1 000 000 circular mil cable. The total weight of copper added in the three places was therefore about 12 113 pounds. The original plan called for the installation, in addition to the above-mentioned feeders, of a 1 000 000 circular mil cable running east on Ann Avenue to Ninth Street, a distance of 2900 feet, and two 1 000 000 circular mil feeders running east from the power house along Ann Avenue to Broadway, a distance of 3800 feet. The total weight of copper under the original plan would have been 60 100 pounds, all of it in 1 000 000 circular mil cables, while in the system as actually completed there were, as is shown later, 72 213 pounds of copper, all of which was of 1 000 000 circular mils cross section except the two short 0000 feeders running to Eighteenth Street and Ann Avenue. The excess cost of the actual system over that of the original system was about $3147, exclusive of the cost of the resistances which is negligible, figuring the cost of overhead feeders at $750 per 1000 feet of 1 000 000 circular mil cable installed. All of the additional feeders were installed overhead, except the two 0000 cables, which were in fiber conduit. The cost of the latter feeder is figured at $1400 per 1000 feet of million circular mils of cable.

In designing these extensions the object was to reduce the potential gradient in the rail return at all points of the system to a value not exceeding 1 volt per 1000 feet, average for one hour at peak load, which at 46 per cent load factor would correspond to an average of about 0.46 volt per 1000 feet during the 24-hour period. In making the tests the system was first arranged as an uninsulated feeder system by tying the tracks at Mississippi and Ann avenues

and Eighteenth Street and Ann Avenue as directly to the bus-bar as the connecting cables would permit. A complete electrical survey was then made to determine the electrical conditions existing in the negative return and pipe systems. These measurements include the following:

1. *Rail-Gradient Measurements.*—These for convenience comprised measurements with a millivoltmeter of the drop of potential on a fixed length of 4 feet of rail, the measurements on all the rails on any particular street being taken at each point. This method involves the assumption that all joints are as good as equivalent length of rail. Numerous preliminary tests of joints were made to determine the condition of the joints and all bad joints found were repaired before final measurements were begun.

2. *Current Flow in Pipes, Including Both Gas and Water Mains.*—For this purpose excavations were made at a number of points and rubber-covered leads were fastened to the pipes 4 feet apart, the leads being brought underground to service boxes located inside the curb. These points were for the most part located within a half-mile of the station. Measurements of the millivolts drop on the pipe at these points permit the calculation of the actual value of the current flow in the pipes at those points, the size and kind of pipe being known. In addition to these, potential measurements were made between adjacent fire plugs at a number of outlying points considerably beyond the terminals of the feeders. While these do not permit the calculation of the actual current flow in those localities the measurements taken under the insulated and uninsulated systems gave values proportional to the current flow under the two conditions, and thus afford a means of determining the relative current flow in the two cases.

3. *Potential Difference Measurements Between Pipes and Rails.*—These measurements were taken throughout a large part of the area affected by the station, including a considerable portion of the region where the pipes were negative to the rails, in order that any tendency of the insulated feeder system to extend the positive area could be determined.

4. *Over-all Potential Measurements.*—These measurements were made between a point on the rails adjoining the power house and a number of remote points near the extreme limits of the feeding districts. These measurements were made with the coöperation

of the Kinloch Telephone Co., which connected the telephone wires to the points at which potential measurements were desired, so that the measurements could all be made at the telephone exchange.

5. *Current in the Various Feeders.*—These data were taken in order to determine the correctness of the current distribution and the economy with which the copper was being worked in the different parts of the system.

After all of the above measurements were completed the system was converted into an insulated feeder system, as mentioned above, and the same measurements repeated at the same points. In taking the electrical measurements at any one point the readings were taken every 15 seconds for a period varying from 5 to 15 minutes, according to local conditions, and the average of all these readings is taken as the reading at that particular time of day.

Since readings at different points were necessarily taken at different hours of the day, when the station load differed, the readings as observed are not directly comparable, and in order to get a basis on which the readings under different conditions could be directly compared it was found most satisfactory to reduce all the readings to the average 24-hour values. This was done by dividing the average observed reading at any point by the ratio of the station load at that particular time of day to the 24-hour average station load. It is this reduced 24-hour average value that is recorded in the tables in each instance. Careful study of a large amount of test data shows that this affords a very satisfactory basis of comparison.

In converting to the insulated feeder system, the different extensions outlined in detail above were installed and the feeders were adjusted for approximately equal drop by the insertion of suitable resistances where necessary. The number and location of these resistances are shown in Fig. 2, which gives the final layout of the insulated feeders. It will here be seen that there are three resistances at the substation in the cables running to the tracks at Mississippi and Ann avenues, Eighteenth Street and Ann Avenue, and Twelfth Street and Ann Avenue. There is also a resistance in the feeder running north on Mississippi Avenue to Mississippi and Geyer avenues, the resistance being at the outer end of the feeder. The feeder running north on Mississippi Ave-

nue to Lafayette Avenue is connected to the tracks at Lafayette and Mississippi avenues through a resistance tap designed to give about 4 volts drop at peak load. There is also a resistance tap at Ann Avenue and Ninth Street. This is not, however, in series with any feeder, but is connected between the feeder which is connected to the tracks at Ninth Street and the two feeders which run on to Broadway. It, therefore, affords a certain measure of paralleling between these feeders.

A comparison of the measurements taken under the insulated and uninsulated feeder systems shows clearly the relative danger from electrolysis under the two systems. Although the amount of copper in the feeder systems under these two series of tests is not the same in each case, the difference was not great enough to produce any marked change in electrolysis conditions under the uninsulated feeder system. This was shown in advance by careful calculations and was borne out by experimental data obtained later, so that although some copper was added for the insulated feeder system, such copper, because of its outlying location, would have exerted practically no influence when used in connection with the uninsulated system. The results show the changes due to conversion from an uninsulated to an insulated system with substantially the same amount of copper.

2. RAIL GRADIENTS

In determining the rail gradients measurements were taken on a fixed length of 4 feet of rail. The points for measurement were selected so as to give the maximum gradients that existed in each case. This means that gradient measurements were taken on all sides of each point at which a negative cable was tapped to the tracks under both the insulated and uninsulated feeder systems. It is obvious that at more remote points the gradients tend to become less than the values recorded at these places, except under very special conditions, which did not exist in this installation. The value of these rail gradients consists chiefly in that they permitted the determination of whether or not the gradients calculated in advance had been approximately realized, and they also afforded a definite indication as to the condition of the track. Since the gradients were measured on all of the rails on a given street, if the tracks were in good condition and properly cross bonded, the

rail-gradient measurements should be substantially equal on all of the rails. If, however, there was a marked difference in gradients on different rails, it indicated that the current was not equally distributed between the rails, which in turn indicated a bad condition of the joints somewhere in the vicinity. The latter was found actually to be the case, and it was necessary to make a considerable number of repairs of the track before satisfactory conditions were finally realized. The location of the points at which potential gradient measurements were taken, and also the values obtained under both the insulated and uninsulated systems, are shown in Table 1.

TABLE 1

Rail Gradients

Location	Uninsulated feeders		Insulated feeders	
	Direction of flow	Gradient volts per 1000 feet	Direction of flow	Gradient volts per 1000 feet
Grattan north of Lafayette			South	0.47
Lafayette east of Grattan			West	0.15
Lafayette west of Grattan			West	0.34
Lafayette east of Mississippi	West	1.90	West	0.59
Lafayette west of Mississippi	East	0.16	East	0.48
Mississippi north of Lafayette	South	0.90	South	0.72
Mississippi south of Lafayette	South	1.87	South	0.75
Mississippi south of Geyer	South	2.89	South	0.57
Geyer east of Mississippi	West	0.91	West	0.29
Geyer west of Mississippi	East	1.17	West	0.60
Mississippi south of Ann	North	1.35	North	0.21
Gravois south of Victor	North	1.77	North	0.17
Victor east of Gravois	East	0.29		
Gravois west of Jefferson	East	0.98	East	0.03
Jefferson north of Gravois	South	0.69	South	0.68
Jefferson south of Gravois	North	0.44	North	0.22
Gravois west of California			East	0.59
California north of Gravois			South	0.33
California south of Gravois			North	0.15
Broadway north of Ann	South	0.59	South	0.44
Broadway south of Ann	North	0.35	North	0.90
Ninth north of Ann	South	0.69	South	1.20
Ninth south of Ann	North	0.14	North	0.39
Twelfth north of Ann	South	0.33	South	0.25
Twelfth south of Ann	North	0.80	North	0.30
Eighteenth north of Ann	South	0.60	South	0.80
Eighteenth south of Ann	North	0.75	North	0.43
Average		0.93		0.46

By comparing the figures point by point in the columns showing average gradients under each system we get the effect produced by the change from uninsulated to insulated feeders. An examination of these columns shows that in many places the gradients have been greatly reduced, this being particularly true in the region near the power house where the gradients were rather high under the uninsulated system.

It will be noted that there is but one point which shows a potential gradient greater than 1 volt per 1000 feet under the insulated feeder system, whereas the average of all points is but 0.46 of a volt. Since the station-load factor is about 46 per cent, this means that the average potential gradient at peak load is almost exactly 1 volt, and most of the readings will not vary much from this mean value. These figures show that the installation of the insulated return feeder system has substantially fulfilled the conditions that it was designed to accomplish in the way of potential gradients, in that the mean value at peak load does not exceed the calculated value of 1 volt per 1000 feet. Under the uninsulated feeder system, however, there are a considerable number of readings which run above 1 volt average, the highest being 2.89 volts per 1000 feet, which corresponds to a peak-load value of about 6.2 volts per 1000 feet. The average for all points under the uninsulated feeder system is 0.93 volt for the 24-hour period, which corresponds to a mean value of 2 volts during peak load.

While it is important that rail gradients should be kept low, this figure is only of indirect importance, since low gradients in general mean small leakage and consequently reduced current flow on the pipes. Of even greater importance, however, than low gradients is the direction of the gradient. Under the uninsulated feeder system this gradient is necessarily continuous from the outlying districts clear into the power house; whereas, under the insulated feeder system, the current flow can, if desired, be made to flow from all directions toward the points of tap of the insulated feeders to the rails, and since these points are distributed through a considerable portion of the feeding area, the direction of current flow in the rails can be frequently reversed, so that the gradient in any one direction will extend over only a compara-

tively short distance, and hence large differences of potential between different points in the earth can not be set up.

It will be evident, therefore, that the improvement in electrolysis conditions caused by the installation of insulated feeders will in general be much greater than the ratio of reduction of the rail gradients. This is borne out in a very marked manner by the data given below.

3. CURRENT FLOW IN PIPES

One of the best criteria for determining the relative amounts of damage from electrolysis under different conditions of track return is afforded by determining the current flow in the pipes. Since, as in the present case, where there were no metallic connections to pipes, all the current flow carried by the pipes must ultimately be discharged into the earth, the total amount of electrolysis will be approximately proportional to the current flow on the pipes.

Table 2 shows the current flow, as measured at a number of points under the insulated and uninsulated feeder systems. The currents in all cases were calculated from measurements of millivolt drop on a 4-foot length of pipe, the resistance of the pipe being determined from the size and kind of pipe and known constants as determined from numerous laboratory tests. This method of determining current in the pipes, while not strictly accurate, because of variations in the kind and weight of the pipes, has, nevertheless, been shown to be sufficiently accurate for most practical purposes when used with care.

Referring to Table 2, the first column, headed "Location," gives the points at which current measurements were made; the second column, headed "Size of pipe," gives the diameter in inches of the pipe on which the current was measured, and in each case this figure is followed by the letter W or G, indicating whether the pipe was a gas or water main. In the third and fourth columns the current flow average for the 24-hour period is given for the two systems.

TABLE 2

Current in Gas and Water Pipes. Not Drained

Location	Size of pipe, inches	Current in amperes	
		Uninsulated system	Insulated system
Russell, west of Thirteenth	30 W	46.80	3.78
Russell, west of Mississippi	6 W	0.60	0.00
Ann, west of Twelfth	4 G	0.16	0.17
Ann, west of Eighteenth	6 W	3.24	1.86
Ann, east of Mississippi	4 G	6.93	2.16
Ann, east of McNair	6 W	2.35	0.05
Ann, east of McNair	4 G	0.17	0.03
Gravois, west of Eighteenth	6 W	11.80	1.63
Gravois, west of Shenandoah	4 G	0.08	0.03
Shenandoah, west of Thirteenth	20 W	9.42	0.62
Shenandoah, east of McNair	20 W	43.10	12.50
Lynch, west of Indiana	6 G	0.15	0.11
Eighteenth, north of Shenandoah	6 W	6.97	3.62
Eighteenth, north of Victor	20 W	23.40	7.48
Lemp, north of Victor	6 G	0.11	0.05
Mississippi, south of Lafayette	6 G	0.06	0.03
Mississippi, south of Allen	20 W	1.40	1.70
Mississippi, south of Russell	20 W	56.40	19.30
Mississippi, south of Ann	20 W	19.60	3.06
Salena, north of Shenandoah	20 W	40.20	7.02
Salena, north of Victor	6 W	0.31	0.10
Total	.....	273.25	65.30

An examination of the columns headed "Current in amperes" shows that there has been a very marked reduction in the current flow in practically all cases. The general average ratio of reduction is best determined by summing up the total current flow in the pipes at all points and determining the ratio of these total currents under the insulated and uninsulated systems. It will be seen from these figures that the total current flow at all observation points under the uninsulated feeder system was 273.3 amperes, whereas the corresponding figure under the insulated feeder system was 65.3 amperes, which gives an average ratio of reduction of about 4.2 to 1. This represents the average reduction in the rate of electrolytic corrosion throughout the system, as indicated by these

measurements. In some localities, particularly near the power station, the reduction will be greater than this, whereas in the more remote districts it will be correspondingly less, but these figures may be taken as a fair indication of the general improvement that is effected by the insulation of the feeders.

EFFECT OF PIPE DRAINAGE ON CURRENT FLOW IN PIPES

While no attempt was made in the present investigation to install a complete pipe-drainage system, it was deemed worth while to temporarily tie in the pipes at points near the station in order to determine the effect of such tying in on the general magnitude of current flow in the pipes, and particularly the relative increase of current produced by such tying in under the insulated and uninsulated feeder systems. For this purpose temporary ties between the water and gas pipes at Mississippi and Ann Avenues and the tracks were installed, and likewise a direct tie between the water pipes and tracks at Twelfth Street and Ann Avenue was installed.

Measurements of current flow at the same places as shown in Table 2 were made with the pipes thus tied in and with the feeders insulated and uninsulated from the ground. The results of these measurements are shown in Table 3. Here the columns have the same significance as in Table 2, the columns 3 and 4 representing the currents in the pipes under the uninsulated and insulated feeder systems, respectively. It will be seen by comparing these figures with those of Table 2 that there has in general been a marked increase in current flow in the pipes, and this is particularly true in the case of the uninsulated system.

The sum of all the currents at different points of measurement is 844 amperes for the uninsulated system and 84.8 amperes under the insulated system, showing that under these conditions of tying in the current flow in the uninsulated system is, on the average, about 10 times as great as under the insulated feeder system. It will also be observed by comparing the totals of Table 2 with those of Table 3 that the tying in of the pipes with the uninsulated feeder system causes an increase in the current flow in the ratio of about 3.1 to 1, whereas under the insulated feeder system the increase in current due to tying the pipes in is increased only in the ratio of 1.3 to 1.

TABLE 3

Current in Gas and Water Pipes. Pipes Drained

Location	Size of pipe, inches	Current in amperes	
		Uninsulated system	Insulated system
Russell, west of Thirteenth	30 W	108.00	5.02
Russell, west of Mississippi	6 W	4.90	0.71
Ann, west of Twelfth	4 G	0.24	0.32
Ann, west of Eighteenth	6 W	5.04	3.15
Ann, east of Mississippi	4 G	9.20	3.53
Ann, east of McNair	6 W	4.79	0.05
Gravois, west of Eighteenth	6 W	21.63	1.98
Ann, east of McNair	4 G	0.34	0.35
Gravois, west of Shenandoah	4 G	0.30	0.08
Shenandoah, west of Thirteenth	20 W	8.82	2.20
Shenandoah, east of McNair	20 W	83.00	20.60
Lynch, west of Indiana	6 G	0.11	0.11
Eighteenth, north of Shenandoah	6 W	9.26	3.37
Eighteenth, north of Victor	20 W	42.80	2.57
Lemp, north of Victor	6 G	0.10	0.05
Mississippi, south of Lafayette	6 G	0.11	0.05
Mississippi, south of Allen	20 W	8.17	1.20
Mississippi, south of Russell	20 W	301.00	22.20
Mississippi, south of Ann	20 W	105.40	6.94
Salena, north of Shenandoah	20 W	128.40	10.23
Salena, north of Victor	6 W	2.55	0.11
Total		844.16	84.82

This shows that the tying in of the pipes has a much smaller tendency to increase the current flow in the case of insulated feeders than it has in the case of uninsulated feeders. The total current flow with the pipes tied in under the insulated-feeder system is only 84.8 amperes, whereas the current flow under the uninsulated system with the pipes not tied in is 273 amperes, which means that draining the pipes at these two points under the insulated-feeder system results in only thirty-one per cent as much current flowing in the pipes as the flow in the pipes without such drainage under the uninsulated-feeder system.

These various ratios are summarized in Table 4 and show in a very striking manner the marked reduction in current flow that in every case accompanies the insulated-feeder system, and they

form an excellent illustration of the value of the insulated feeders as against the uninsulated-feeder systems as a means of reducing electrolysis trouble.

TABLE 4

Summary of Current in Pipes and Current Flow Ratios

CURRENT IN PIPES

	Amperes
Uninsulated system, pipes drained, total current	844.1
Uninsulated system, pipes not drained, total current	273.2
Insulated system, pipes drained, total current	84.8
Insulated system, pipes not drained, total current	65.3

CURRENT FLOW RATIOS

$$\frac{\text{With insulated feeders}}{\text{With uninsulated feeders}} = \frac{\text{Pipes not drained}\ 65.3}{273.2} = 0.239 \qquad \frac{\text{Pipes drained}\ 84.8}{844.1} = 0.101$$

$$\frac{\text{With pipes drained}}{\text{With pipes not drained}} = \frac{\text{Insulated feeders}\ 84.8}{65.3} = 1.30 \qquad \frac{\text{Uninsulated feeders}\ 844.1}{273.2} = 3.09$$

$$\frac{\text{Insulated feeders, drained pipes}}{\text{Uninsulated feeders, pipes not drained}} = \frac{84.8}{273.2} = 0.31$$

The above figures show the current flow in the pipes in the region within approximately a quarter of a mile radius of the power station. It was deemed advisable also to determine the relative current flow under the different conditions at points more remote from the power house, and for this purpose, in order to avoid the labor of additional excavations, potential measurements were made between adjacent fire hydrants at suitable places, the potential differences under the insulated and uninsulated systems being taken as representing the relative current flow in the two cases. Under each feeder system also these measurements were taken with the pipes drained at the two points mentioned above near the station, and also with the pipes not drained, so as to show the tendency, if any existed, of pipe drainage to increase current flow in the pipes at very remote points. These data are given in Table 5.

TABLE 5

Potential Differences Between Fire Plugs

Location			Average volts			
			Uninsulated feeders		Insulated feeders	
On—	From—	To—	Pipes not drained	Pipes drained	Pipes not drained	Pipes drained
Mississippi	Kennett	Lafayette	0.685	0.908	0.042	0.059
Mississippi	Allen	Geyer	.211	.425	.150	.137
Gravois	Sidney	Victor	.646	.735	.229	.260
Ann	Menard	Eleventh	.320	.624	.159	.208
Ann	Jefferson	Indiana	.132	.308	.060	.023
Shenandoah	Indiana	Missouri	.394	.648	.159	.219
McNair	Lynch	Sidney	.156	.333	.001	.007
Total			2.544	3.983	0.800	0.913

POTENTIAL DIFFERENCE RATIOS

$$\frac{\text{With insulated feeders}}{\text{With uninsulated feeders}} = \frac{\text{Pipes not drained } 0.800}{2.544} = 0.314 \qquad \frac{\text{Pipes drained } 0.913}{3.983} = 0.229$$

$$\frac{\text{With pipes drained}}{\text{With pipes not drained}} = \frac{\text{Uninsulated feeders } 3.983}{2.544} = 1.56 \qquad \frac{\text{Insulated feeders } 0.913}{0.800} = 1.14$$

$$\frac{\text{Insulated feeders, drained pipes}}{\text{Uninsulated feeders, pipes not drained}} = \frac{0.913}{2.544} = 0.359$$

In this table are shown the voltage drops between hydrants, under both the insulated and uninsulated feeder systems, and under each system are shown also the voltage drops with the pipes drained and not drained. The ratio of the sums of the voltage drops with the insulated and uninsulated systems is 0.314 with the pipes not drained. Under pipe drainage the difference is still more marked, the ratio of the sums of the volt drops being here only 0.229. With the insulated feeder systems the ratio of current flow with the pipes drained and not drained is 1.14. With the uninsulated feeder system the ratio is 1.56, indicating that even in these more remote points the current flow shows a marked increase when the pipes are tied in, but that this increase is much less marked in the case of the insulated feeder system than it is in the case of the uninsulated feeder system. The last ratio given in

the summary of Table 5 also shows that at these outlying points the current flow in the pipes, under the insulated feeder system combined with pipe drainage at the points near the power house, is but little over a third of the current flow without pipe drainage under uninsulated feeder systems.

We wish to emphasize here the fact that in making the above tests with the pipes tied in, no attempt was made to install a scientific pipe drainage system with a view of obtaining minimum current flow in the pipes. If this had been done, the current flow under pipe drainage could no doubt have been materially reduced, particularly at points near the power house, but such reduction would not have occurred in the outlying points referred to under Table 5. The results as presented, however, while they do not show conditions that would exist under an ideal pipe drainage system, show, nevertheless, the tendencies which exist, and that conditions in regard to current flow in the pipes are invariably much better under the insulated feeder system than under the uninsulated system.

One point of special interest in connection with the data on current flow in the pipes should be mentioned here. By reference to Tables 2 and 3 it will be noted that those points marked W in column 2, indicating water mains, show in general a much higher current flow than the points marked G, which indicate gas mains. The reason for this is that the gas mains in this vicinity have a considerable number of cement joints, and this undoubtedly is responsible for the comparatively low current flow. It is probable that those points which show almost no current flow are sections which contain cement joints, whereas those points that show small yet appreciable current flow are older and lead-jointed sections, since both kinds are known to exist in this territory.

4. POTENTIAL DIFFERENCES BETWEEN PIPES AND RAILS

Another criterion for determining the relative danger to pipes under different conditions is the potential differences between pipes and rails. Such measurements do not give altogether reliable indications as to relative danger when made in different localities, because of differences in soil resistance and other local conditions, but when such measurements are made at the same

points under different physical conditions of the negative return the values afford an accurate measure of the relative danger from electrolysis. Such potential difference measurements were, therefore, made between fire hydrants and rails at a considerable number of points under both the insulated and uninsulated feeder systems, and the results are given in Table 6.

TABLE 6

Potential Differences Between Pipes and Rails

A. POTENTIALS ORIGINALLY OVER ONE VOLT

Location	Potential difference		Location	Potential difference	
	Uninsulated system	Insulated system		Uninsulated system	Insulated system
Twelfth and Russell...	1.80	0.70	Mississippi and Allen..	3.45	0.37
Eighteenth and Geyer..	1.38	0.29	Mississippi and Russell.	4.22	0.17
Eighteenth and Allen...	2.02	0.67	Mississippi and Gravois.	3.60	0.16
Eighteenth and Russell.	3.00	0.24	Gravois and McNair....	3.20	−0.84
Eighteenth and Ann....	2.15	0.08	Gravois and Victor.....	1.13	0.53
Eighteenth and Shenandoah.....	2.02	0.70	McNair and Geyer.....	1.91	0.15
Eighteenth and Victor..	1.69	0.55	Average.....	2.44	0.33
Mississippi and Geyer..	2.63	0.86			

Ratio of average values=7.4.

B. POTENTIALS ORIGINALLY LESS THAN ONE VOLT

Ninth and Lafayette....	0.62	0.02	McNair and Victor.....	0.94	0.52
Twelfth and Shenandoah.....	0.56	0.59	Salena and Victor.....	0.71	0.40
Grattan and Lafayette...	0.25	0.30	Jefferson and Lafayette..	0.22	−0.01
Eighteenth and Lafayette.....	0.38	0.05	Jefferson and Geyer....	0.06	−0.04
Eighteenth and Sidney..	0.69	0.25	Jefferson and Ann.....	0.00	−0.01
Mississippi and Lafayette.....	0.62	0.37	Jefferson and Gravois...	0.77	0.77
Lemp and Victor.....	0.71	0.35	Jefferson and Pestalozzi.	0.39	0.32
			Average decrease..	0.49	0.28

Ratio of average values=1.75.

C. POTENTIALS ORIGINALLY NEGATIVE

Broadway and Victor...	−0.70	+0.48	Grattan and Park.....	−0.51	+0.35
Broadway and Russell..	−0.01	+0.80	California and Geyer....	−0.01	+0.29
Ninth and Russell.....	−0.23	+0.80	California and Gravois..	−0.33	+0.84
Ninth and Victor.....	−0.33	+0.62	Average.....	−0.31	+0.56
Eleventh and Park.....	−0.37	+0.33			

An examination of these data reveals that for the most part there has been a marked reduction in potential differences, particularly in the region near the power house where such potential differences were originally high. In order to facilitate the interpretation of these data they have been divided into three groups with subheads A, B, and C. The data for all points at which original potential differences were greater than 1 volt are placed in group A; all those at which the pipes were positive but less than 1 volt are placed in group B; and all those points at which the pipes were originally negative but have become somewhat positive under the insulated feeder system are placed in group C.

On examination of group A, which includes the points of high original potential and therefore covers the area in which the original danger was greatest and the need for improvement most urgent, we find that there has been a very large reduction of potential differences between pipes and rails. In one case, notably at Gravois and McNair avenues, where the pipes were originally strongly positive to rails, they have become slightly negative, and in all the other points in this group a marked reduction is apparent. The average potential difference at all points under the uninsulated system was 2.44 volts, whereas under the insulated feeder system this average was reduced to 0.33 volt, giving a mean ratio of reduction of 7.4 to 1.

Referring to group B, where the original potential differences were less than 1 volt, we find there is still a very considerable reduction. The average for all of these points is 0.49 volt, whereas the average for the corresponding points under the insulated feeder system is 0.28 volt, giving a ratio of reduction of 1.75 to 1. Even here, in the intermediate region, where the danger was comparatively small under the original conditions, there has still been a considerable improvement, the average value of 0.28 volt being so small as not to involve any considerable danger to the pipes.

In group C we find that eight points which were originally negative have become more or less positive. This is to be expected in general because of the tendency to form positive areas in the region near the points where the negative feeders are tied to the

track. At these eight points there existed originally a mean value of potential difference of -0.31 volt, whereas under the insulated feeder system this has been converted into a mean value of $+0.56$ volt. In the more remote districts the potential differences were negative under both insulated and uninsulated systems, and are therefore of no consequence here.

These data show that under the insulated feeder system the reduction of danger is greatest at those points where there is greatest need for improvement, and the foregoing figures indicate very clearly that in the present instance the potential differences have been reduced to so low a value as to make the pipes comparatively safe. They also show that although the installation of a negative feeder system does tend to increase the area of the positive zone the positive potentials are so low as to lead to no serious consequences. One of the principal objections to the installation of insulated negative feeders that has been urged by some engineers has been that it creates a large number of positive areas covering a much greater territory than is the case with the ordinary uninsulated system. Although it is true that there is a tendency for the insulated feeder system to extend the positive area, and this is clearly indicated by the foregoing data, these data nevertheless show that comparatively few new positive points have been created, and that where they have appeared, the potential differences are so low as not to give rise to any serious corrosion of the pipes under ordinary conditions. The figures show conclusively that this objection to the insulated negative feeder system is not valid, at least in the present case, whereas the reduction of the potential differences in the regions where the conditions were originally bad is so great as to completely overshadow the effects of the slight tendency to broaden the positive zone.

All of the foregoing potential difference measurements were taken between water pipes and rails because of the greater convenience of making such measurements, since measurements could be taken between fire hydrants and tracks. In order to determine whether or not the potential differences between gas pipes and the tracks differed materially from the corresponding

voltages between water pipes and rails, a considerable number of measurements were taken between water and gas mains at accessible places. These measurements are shown in Table 7. These figures show that potential differences between water and gas mains are in nearly all cases very low, the maximum observed anywhere being 0.56 volt average for the 24-hour period, and the great majority being much smaller than that figure, the mean of all the measurements taken being 0.147 volts average for 24 hours. These figures show that potential differences between the gas pipes and rails are not much different from the values observed and recorded above for the water pipes.

TABLE 7

Potential Differences Between Water and Gas Pipes [2]

Location	Uninsulated feeders, average volts	Location	Uninsulated feeders, average volts
Eighteenth and Geyer	0.00	Selena and Victor	0.21
Eighteenth and Allen	0.05	Gravois and Shenandoah	−0.12
Eighteenth and Russell	0.05	Gravois and Victor	0.22
Eighteenth and Shenandoah	0.27	McNair and Geyer	0.02
Eighteenth and Victor	0.17	McNair and Allen	0.04
Lemp and Shenandoah	0.02	McNair and Russell	−0.09
Lemp and Victor	0.16	McNair and Ann	0.06
Mississippi and Geyer	0.09	Missouri and Ann	0.07
Mississippi and Allen	0.16		
Mississippi and Russell	0.44	Average	0.147
Mississippi and Gravois	0.56		

[2] Water pipes taken as positive

5. OVER-ALL POTENTIALS

Still another important factor in determining the probability of current being taken up by the pipes is the maximum potential differences occurring between the tracks near the station and remote points in the track network. Accordingly, a considerable number of measurements of over-all potentials were taken under both the insulated and the uninsulated feeder systems. These data are shown in Table 8.

TABLE 8

Over-All Potentials

[Voltages referred to tracks at Mississippi and Ann Avenues]

Location of outlying contact	Distance, thousand feet	Uninsulated feeders		Insulated feeders	
		Total volts	Volts per 1000 feet	Total volts	Volts per 1000 feet
Broadway and Chouteau	8.7	11.5	1.3	2.7	0.31
Broadway and Park	6.9	11.0	1.6	3.0	0.44
Broadway and Victor	5.0	11.3	2.3	0.3	0.06
Broadway and Arsenal	7.6	11.1	1.5	0.2	0.03
Ninth and Park	6.1	10.1	1.7	1.6	0.26
Ninth and Victor	4.1	10.2	2.5	−0.2	−0.05
Ninth and Pestalozzi	5.8	10.1	1.7	0.1	0.02
Twelfth and Chouteau	6.3	11.3	1.8	3.3	0.52
Twelfth and Park	4.8	9.3	1.9	2.6	0.54
Twelfth and Sidney	3.2	6.3	2.0	−0.1	−0.03
Eighteenth and Chouteau	5.4	11.3	2.1	2.7	0.50
Eighteenth and Park	4.2	8.3	2.0	2.6	0.62
Lemp and Arsenal	3.8	6.9	1.8	0.7	0.18
Jefferson and Park	5.4	11.3	2.1	2.8	0.52
Jefferson and Geyer	3.2	11.0	3.4	0.8	0.25
Jefferson and Arsenal	4.4	7.1	1.6	−1.1	−0.25
Jefferson and Cherokee	6.4	10.2	1.6	0.0	0.00
California and Chouteau	7.9	10.7	1.4	3.6	0.46
California and Shenandoah	3.4	10.0	2.9	1.2	0.35
California and Gravois	4.0	10.3	2.6	0.8	0.20
Compton and Arsenal	6.2	13.5	2.2	3.6	0.58
Grand and Arsenal	8.1	15.3	1.9	5.1	0.63
Averages	.....	10.4	2.0	1.8	0.31

In this table column 1 gives the location of the outlying point. Column 2 gives the distance of the outlying points in thousands of feet from the point on the tracks near the station, this distance being measured along the streets by the shortest route. Column 3 gives the average potential difference between the two points. Column 4 is the total over-all potential of column 3 divided by the distance shown in column 2, and is therefore the average potential gradient in volts per thousand feet. A comparison of the potential differences and the volts per thousand feet under the uninsulated feeder system with the corresponding figures for the insulated feeder system shows the uniformly great reductions in the latter case.

An examination shows that the average over-all potential differences under the uninsulated feeder system is 10.4 volts, whereas the average over-all potential difference under the insulated feeder system is but 1.8 volts, a reduction in the ratio of approximately 6 to 1. The average gradient under the uninsulated system is 2.0 volts per 1000 feet, while under the insulated feeder system it is but 0.31 volt per 1000 feet, showing an average ratio of reduction of almost 7 to 1. These figures are in accord with all of the other data presented above, and they confirm the conclusion that a very marked improvement has accompanied the conversion of the system from uninsulated to insulated feeders.

6. SIGNIFICANCE OF TEST DATA

An examination of the preceding data on current flow in the pipes, potential differences between pipes and rails, and over-all potential differences shows that under the insulated negative feeder system these values range from one-half to one-seventh of the corresponding values which prevail under the uninsulated feeder system. These ratios represent approximately the difference in electrolysis damage that would result in the two cases.

Under ordinary conditions as they were found to exist under the uninsulated feeder system, it is probable that serious trouble from electrolysis would not have become manifest in this new district for perhaps 5 or 10 years, and if the rate of electrolytic corrosion is reduced under the insulated feeders to an average of, say, one-fifth of the original rate as indicated by the figures, the length of time that would elapse before trouble would begin to be serious would be of the order of twenty-five to fifty years. This period is so long that, for the most part, the pipes would require replacement for reasons other than electrolytic corrosion, and if such were the case the life of the pipes would not be shortened to any appreciable extent by electrolysis damage; so that the conditions shown by these tests seem to indicate that under the insulated feeder system the danger has been reduced to almost a negligible quantity.

This statement, however, should be accepted with some caution, because our investigations show that the numerical value of the potential difference between pipes and rails is not an altogether reliable measure of the rate at which damage progresses because of

variations in soil conditions. The figures are nevertheless instructive when considered as applying to average conditions, with the understanding that in special cases (and possibly in the present case) soil conditions may be such that even with the low potential differences which prevail here appreciable corrosion may still result, although the rate at which damage progresses will be but a small fraction of what it would be if uninsulated feeders were used.

The all-important conclusion to be drawn from the foregoing tests is that, regardless of what local conditions may be as regards soil conditions, the rate of damage under the insulated feeder system will be reduced to a fraction of what it would be with substantially the same amount of copper used as uninsulated feeders in parallel with the tracks.

In case experience should show that an appreciable amount of electrolysis still occurred under the insulated feeder system as now installed, we would not recommend pipe drainage in the present instance to take care of this residual trouble, primarily because of the large number of insulating joints in the gas mains. We think it would be much more effective to take care of any residual trouble that may exist by some slight extensions of the insulated negative feeder system. As for lead-covered cables, it is probable that a certain amount of drainage will always be necessary for their adequate protection, but a much smaller amount of current will need to be drawn from them under the insulated feeder system than under an uninsulated system.

7. DISCUSSION OF COSTS

COMPARISON OF COSTS OF INSULATED AND UNINSULATED FEEDER SYSTEMS AS ACTUALLY INSTALLED

The foregoing experimental data give a comparison between the insulated and uninsulated negative feeder systems on the basis of approximately the same amount and distribution of copper in each case. In dealing with the question of electrolysis mitigation, however, it is necessary to consider not only the protection secured, but also the cost of securing such protection. In Table 9 we give a detailed statement of the amount of copper in each of the insulated negative feeders as now installed, together with their

location, whether overhead or underground, and the estimated cost of installation. In calculating this cost we have assumed that the cost of installing overhead feeders is uniformly $750 per 1000 feet of 1 000 000 circular mil cable, including the cost of copper and of installation charges. For underground construction the figure of $1400 per 1000 feet of 1 000 000 circular mil cable has been used. These figures will, of course, vary somewhat, according to conditions, but they represent fair average values.

TABLE 9

Approximate Cost of Insulated Feeders, Ann Avenue Substation

Location of feeder terminal	Length, feet	Size in million circular mils	Character	Total cost installed
Lafayette and Grattan	3600	1	Overhead	$2,700
Mississippi and Geyer	1300	1	do	975
Gravois and Jefferson	2300	1	do	1,725
Gravois and California	3900	1	do	2,925
Ann and Broadway	3800	2	Underground	10,640
Ann and Ninth	2900	1	do	4,060
Ann and Twelfth	1450	1	do	2,030
Ann and Eighteenth	760	0.42	do	447
Total				25 502

Rated capacity of station, 4000 kilowatts: cost per kilowatt, $6.38.

It will be seen from an examination of Table 9 that the total cost of the negative feeders installed for this station is $25 502; the rated capacity of the station is 4000 kilowatts, giving a cost of $6.38 per kilowatt of rated capacity as the cost of the negative feeder system. Based on the same unit costs, however, we found that the cost of the original uninsulated feeder system amounted to $22 355, so that the extra cost properly chargeable against the insulated feeder system in this case is the difference between these, or $3147. In addition to the cost of copper we must also consider the value of the energy lost in the negative return.

On an examination of the data given above on the over-all potential measurements in the negative return, we find that under the uninsulated negative feeder system the mean voltage drop on the negative side was 12.2 volts, including the drop on the connections between bus-bar and tracks at the station, while under the

insulated negative feeder system, with the present amount of copper, this negative drop is increased to 19.5 volts. The net increase in negative drop has therefore been 7.3 volts. The 24-hour average current for this station is 3500 amperes, and multiplying this by the increase in voltage drop we find a net increase of power loss on the negative return of 25.55 kilowatts. Multiplying this by 8760, the number of hours in a year, we get a total of 223 818 kilowatt hours per year, which, at 1 cent per kilowatt hour, has a value of practically $2238.

The excess cost of installing the insulated feeder system over the uninsulated system was found above to be $3147, and figuring the annual cost, including interest, depreciation, taxes, etc., at 10 per cent, this amounts to $315, which, added to the $2238 representing the value of energy losses, gives a total annual cost of $2553, which is properly chargeable against the insulated system as it now stands. It should be emphasized, however, that this increase in cost is not a necessary increase, and results only from the plan that was followed of keeping the initial investment as low as possible until the experimental tests could be made.

It should be pointed out that the amount of copper now in the feeder system is such as would give a maximum economy for a maximum station output of about 3000 kilowatts, whereas the actual maximum output of the station is about 4500 kilowatts, or 50 per cent in excess of that for maximum economy. In order to get the most economical negative return system, therefore, we should increase the cross section of the present feeders by approximately 50 per cent on the average, and this would require a total increase in installation cost of approximately 50 per cent, or $12 750, which, added to the excess cost of the present system over the uninsulated system as given above, namely, $3147, gives a total increased installation cost properly chargeable to the insulated feeder system of $15 897, and 10 per cent annual charge on this gives an annual cost on the feeder installation of $1590.

At the same time, since the cross section of the feeders has been increased about 50 per cent, the drop in the negative return will have been reduced to two-thirds of its present value of 18.9 volts, giving a negative drop of 12.6 volts, which is substantially the same as the drop under the uninsulated system. In that case

there would be no appreciable change in the energy losses; consequently the above annual charge of $1590 on the installation cost represents the actual annual cost properly chargeable against the insulated feeder system. It will thus be seen that the addition of $12 750 worth of copper to the present insulated feeder system would save $2238 per year in energy losses, or about 17.5 per cent on the investment.

It is apparent, therefore, that it would be very desirable from an economic standpoint to make this increase in negative copper. In point of fact it would probably be desirable to add even more than this amount of copper, since by so doing the saving in energy loss would, up to a certain point, almost balance the increased annual cost of the installation, and thus the total annual cost would be but slightly increased, and at the same time a large reserve capacity for future growth would be had in the negative feeder system.

COMPARISON OF COSTS OF INSULATED AND UNINSULATED FEEDER SYSTEMS FOR THE SAME VOLTAGE CONDITIONS IN BOTH CASES

It is also very instructive to make a comparison of the relative costs of the two systems based on identical voltage conditions in the track return. Under the insulated feeder system the average gradient in the tracks has been reduced to 0.46 volt per 1000 feet, and if the same condition is to prevail under the uninsulated feeder system it will be necessary to have the same current distribution in the track. Consequently, we must run feeders to the same points and take off the same number of amperes from the tracks at each point, and since the feeders will be in parallel with the tracks we must further give the feeders sufficient cross section, so that they will carry this current back to the bus-bar with an average potential gradient not exceeding 0.46 volt per 1000 feet. In order to determine the amount of copper required to produce the same conditions under an uninsulated system as we have under the insulated system, it is only necessary to determine the average current carried by each feeder under the present insulated system, and calculate the amount of copper that will be required in that feeder to carry the same current with an average gradient of 0.46 volt per 1000 feet. A calculation of this sort has been made and the data are given in Table 10.

TABLE 10

Relative Cost of Insulated and Uninsulated Feeders for the Same Voltage Conditions

Feeder	Present amount of copper (thousand feet of million circular mil cable), insulated system	Average current, amperes	Amount of copper required for average gradient of 0.46 volt per 1000 feet, uninsulated system
Lafayette between Mississippi and Grattan	1.3	120	3.66
Mississippi between Ann and Lafayette	2.3	365	19.70
Mississippi between Ann and Geyer	1.3	231	7.05
Gravois btweeen Ann and Jefferson	2.3	510	27.52
Gravois between Mississippi and California	3.9	342	31.30
Ann between Mississippi and Broadway	7.6	984	87.78
Ann between Mississippi and Ninth	2.9	465	31.68
Ann between Mississippi and Twelfth	1.45	120	4.08
Ann between Mississippi and Eighteenth	0.32	207	1.55
Ann between Mississippi and substation	.....	156	.....
Total	23.37	3500	214.32

Ratio of copper required, $\frac{\text{uninsulated system}}{\text{insulated system}} = \frac{214.32}{23.37} = 9.16$

Summing up the totals of columns 2 and 4 we find that under the insulated system we have a total of 23.37 thousand feet of million circular mil cable; whereas to give identical voltage conditions under the uninsulated feeder system we would require 214.32 thousand feet of million circular mil cable. This shows that for the same voltage conditions it would require 9.16 times as much copper for the uninsulated feeder system as is required in the present insulated system.

Since the cost of the present system is $25 500, the cost of the uninsulated system using the same unit cost would be 9.16 times as great, giving a total of $233 580, which is $208 080 in excess of the total cost of the present insulated feeder system, and figuring as before 10 per cent as the annual cost on the copper installed, we get $20 808 per year as the excess annual charge on the investment in uninsulated feeders. If such a system were installed, however, it can be shown that it would reduce the potential drop in the negative return to about 2 volts, which would be a reduction of 17 volts below that which prevails at the

present time, which corresponds to an annual saving in energy of 521 220 kilowatt hours, which is worth $5212 at 1 cent per kw. hr. Deducting this from the annual charge on the copper we get a net annual charge on the uninsulated feeder system of $15 596 in excess of the annual charge on the present system. While of course it does not follow that if the uninsulated system were to be installed that the location of the feeders would be just the same as here assumed, the assumption is nevertheless approximately true, and the estimated costs are of the correct order of magnitude, and they show the impossibility, from an economic standpoint, of securing with the uninsulated feeder system approximately the same voltage conditions as can be obtained with a system of insulated feeders.

When the advantages from both the electrolysis and economic standpoints are fully weighed it seems rather surprising that insulated feeder systems have not been more widely used in the past, and we are confident that when the advantages are fully appreciated such systems will be adopted as the standard of practice, to the practical exclusion of uninsulated feeders, except in special cases where the load is so light that neither electrolysis conditions nor economic considerations require additional conductivity over that furnished by the tracks themselves.

8. APPLICABILITY OF INSULATED FEEDER SYSTEMS TO OLD STATIONS

It may be questioned whether the foregoing conclusions apply equally well to the case of an old station in which a considerable amount of negative copper has already been installed in the form of uninsulated feeders. If this copper is overhead or in conduit, it can of course be readily converted into insulated feeders at a negligible cost, so that in such a case there is no question but that the foregoing remarks would apply. If, however, the uninsulated copper is laid underground in concrete, or in such other manner as to make it impracticable to remove it or insulate it, this copper would have to be left in the form of uninsulated feeders. If there is already in place enough of such uninsulated copper to give satisfactory conditions as regards voltage drop, of course nothing additional would be required. But if the conditions are such

that it is necessary, in order to secure adequate electrolysis protection, to still further lower the voltage drops, it will be obvious from the foregoing discussion that such lowering of the gradient can be accomplished in a much more economical manner by installing the additional copper in the form of insulated feeders instead of connecting them in parallel with the feeders already in place. The old copper already installed would then be worked at a lower current density, and consequently would be used less efficiently than before, *but no less efficiently than it would be if the same voltage conditions are realized by the addition of more uninsulated copper.*

There appears to be no question, therefore, that in all cases where it is necessary to lower the potential gradients below the values already existing, such lowering of the gradients can be accomplished more economically by putting all the additional copper in the form of insulated feeders.

9. SUMMARY

The experimental data and discussion presented in the foregoing paper appear to warrant the following conclusions:

1. For substantially the same installation cost very much better electrolysis conditions can be secured with insulated negative feeders than with uninsulated feeders.

2. When the potential differences in the track return are reduced to the low values that can readily be obtained by means of insulated negative feeders, the tying in of the pipes to the tracks has a much smaller tendency to cause heavy current flow in the pipes than if such reduction of potential differences is not realized.

3. Where good voltage conditions in the negative return are maintained, the insulated feeder system can, in most cases, be installed so as to yield far greater economies both in installation and operation costs than is possible with uninsulated feeders.

4. In the case of old stations in which there is already a large amount of negative copper installed in such a way that it is impracticable to insulate it, the insulated feeder system would still be economical in case it is desired to lower potential differences in the negative return below those at present existing. Wherever

such reduction of potential differences is contemplated the insulated feeder system will show the same marked economy over the uninsulated system as is shown in the case of new stations.

5. Negative feeders which are so laid that they can not be insulated will not be used any less efficiently if supplemented by insulated feeders than if uninsulated feeders are added, provided equally good voltage conditions in the track are maintained in both cases. The opinion that such uninsulated copper is largely wasted if supplemented by insulated feeders is, therefore, based on a misconception. Uninsulated negative feeders are always wasteful wherever good voltage conditions in the negative return are required, and any addition to such uninsulated feeders is an extension of this waste; this can be avoided by using insulated negative feeders for all extension work.

In conclusion, the writers desire to express their appreciation of the coöperation extended to them by the officials of the United Railways Co., the Laclede Gas Co., city water department, and both the Southwestern and the Kinloch Telephone companies, all of whom did everything possible to assist us in our work. In particular we wish to commend the generous attitude of the officials of the United Railways Co., who willingly incurred considerable expense in connection with the installation of the feeder system, in order that the experiments could be carried out under satisfactory conditions.

WASHINGTON, December 27, 1913.