ELECTRIC FISH SCREEN

By F. O. McMillan

Associate Professor of Electrical Engineering, Oregon State College

CONTENTS

FISH-PROTECTION PROBLEM

Every year millions of game fish and fry of anadromous food fish are carried out on the fields and left to die because they have followed some irrigation canal instead of the main stream channel. Many others are killed by mechanical injury or sudden pressure change incident to passing through hydraulic turbines. The problem of protecting fish from these dangers is not new but probably is as old as the knowledge of irrigation. However, as irrigation and power projects increase in size and number and the supply of fish is depleted, the problem commands greater attention. As early as 1895, Dr. C. H. Gilbert, of Stanford University, called the attention of Hollister D. McGuire (then fish and game protector of Oregon) to the destruction of blueback-salmon fry on the irrigation projects near Wallowa Lake (McGuire, 1896). This led to legislation in Oregon requiring the screening of waterways dangerous to fish. Virtually without exception the biennial reports of the fish and game commissioners since that time have stressed the importance of fish screens.

Two classes of fish of quite different habits are involved in the problem of fish protection. They are those of anadromous habits, such as the salmon and steelhead trout, and those that confine their migration entirely to fresh water. Sportsmen are interested in both classes, while the commercial fishermen, especially in the West, are interested almost entirely in fish that mature at sea.

Of the anadromous fish, the various species of salmon are by far the most important on the Pacific coast. Their habits are such that they are particularly susceptible to destruction, due to unnatural waterway conditions. Artificial stream barriers prevent the mature fish, returning from the ocean, from reaching their spawning beds in the headwaters of the streams. This necessitates the construction of fishways around or over these barriers. The young salmon fingerlings, when impelled by instinct to migrate seaward, are confronted by the peril of destruction in large numbers by entering irrigation ditches, canals, mill races, and other dangerous watercourses. This danger can be eliminated only by the proper protection of the entrances to these waterways. This is not an easy task, especially if mechanical screens are used, because ¼-inch mesh is required to give protection to the very young fry in the yolk-sac stage. The largest salmon to which protection would have to be afforded during their seaward migration would probably be the yearling chinook salmon. Dr. Willis H. Rich has found that the average length of yearling chinook salmon is approximately 4 inches (100 millimeters), both in the Columbia and Sacramento Rivers (Rich, 1920). It is obvious, then, that if mechanical screens were constructed to protect only the yearling salmon, the mesh would be small and the accumulation of leaves and débris would be a constant menace to the flow of water through the screen. What is true of the screens for the protection of salmon is likewise true of screens for protecting the fish living exclusively in fresh water. Some of the larger sizes of these fresh-water fish could be protected by screens of larger mesh. This would make the screen slightly less susceptible to the accumulation of débris. However, such screens obviously would offer only partial protection.

PROTECTIVE LAWS

Adequate laws have been enacted by the legislatures in all of the States having this fish-protection problem. These laws give all legal authority necessary for the protection of the entrances to dangerous waterways if satisfactory devices are available with which to screen them. A typical example of such laws is found in section 61 of the game laws of Oregon, quoted here:

> Any person owning, in whole or in part, or leasing, operating, or having in charge any irrigation ditch, or canal, mill race, or other artificial watercourse, taking or receiving its waters from any river, creek, or lake in which fish have been placed or may exist, shall, upon order of the State game commission, place or cause to be placed, and shall maintain, to the satisfaction of the State game commission, over the inlet of such ditch, canal, mill race, or watercourse, a grating, screen, or other device, either stationary or operated mechanically, of such construction, fineness, strength, and quality as shall prevent any fish from entering such ditch, canal, mill race, or watercourse, to the satisfaction of the State game commission. But before said State game commission shall adopt any permament plan for a screen or device to be placed in irrigating ditches, it shall be its duty to conduct a competitive examination, and at such examination all persons desiring to do so may

submit to said State game commission, for its approval or rejection, working models of its [their] respective screens or other devices for the protection of fish. Inadequate screening devices may be ordered removed and new screens ordered installed when, upon investigation by the State game commission or any of its representatives, it is determined that any screen, grating, or other device, either by construction, operation, or otherwise, is found to be inadequate by the State game commission. In the event the owner in whole or in part, or person leasing, operating, or having in charge such ditch, canal, mill race, or other artificial watercourse, shall fail or refuse to comply with the instructions of the State game commission with respect to the installation, maintenance, or repair of such screen, grating, or other device within such reasonable time as may be specified by the State game commission, he shall be guilty of a misdemeanor, and said State game commission or any of its representatives shall have power to close forthwith the head gates or place such other barrier or obstruction in such ditch, canal, mill race, or other artificial watercourse as said State game commission may deem necessary to prevent the flow of water through such ditch, canal, mill race, or other artificial watercourse until a screen, grating, or other device shall be placed therein to the satisfaction of the State game commission.

From the above law it is obvious that there is nothing lacking in the way of legal authority for the protection of fish from dangerous waterways. Unfortunately, however, the effectiveness of these laws has been impaired greatly because adequate screens have been expensive to install and very difficult to maintain.

MECHANICAL SCREENS

Mechanical screens of the stationary type, having a mesh of sufficient fineness to afford adequate protection to fish fingerlings, have been found very difficult and expensive to maintain. The chief difficulties are the constant accumulation of leaves and débris and mechanical injury to the screen by large floating pieces of débris.

The objectionable features of the stationary-type mechanical screen have been reduced greatly by the revolving, self-cleaning type of screen, which has been available since 1918. However, the revolving screen has not solved the fish-protection problem and leaves much to be desired in the screening of dangerous waterways.

ELECTRIC SCREEN

The idea of using an electrified area in water to direct the movements of fish is not new. At least three and perhaps more United States patents have been granted on methods of using electricity for this purpose. The most recent of these patents was applied for in March, 1922, and was granted in November, 1924 (Burkey, 1924). Hence, no claim is made that the idea of an electric fish screen is new or novel.

Many installations have been made of electric fish "stops" in Washington, Oregon, and California. Some of these installations have been considered successful; others have been pronounced absolute failures. As a result of these conflicting opinions, the electric fish "stop" came into disrepute in some localities and in some instances was abandoned entirely as impractical. Investigation disclosed the fact that, virtually without exception, the installation of electric "stops" had been made by those who had little or no knowledge of electricity, and there was an absolute dearth of information about the voltage gradients fish were susceptible to in water and the voltage gradients required to produce paralysis and death. The only fact that was known definitely was that virtually every installation succeeded in killing some fish. Hence, the electric fish "stop" rapidly gained a reputation as a destroyer rather than a preserver of fish. In the light of these facts, J. E. Yates, assistant engineer of the Pacific Power & Light Co., determined to have an investigation made to find, as far as practical, the facts about the electric fish screen. The results of this investigation are given in this report.

ACKNOWLEDGMENTS

Thanks are due especially to J. E. Yates for advice, assistance, and suggestions given during the investigation. Both the Oregon Fish Commission and the Oregon Game Commission have shown great interest in the experiments. The Oregon Fish Commission very generously lent facilities at the Bonneville fish hatchery and provided the fish used in the experiments. Eugene Howell, superintendent of the Bonneville hatchery, and his assistants gave invaluable help with the experimental work. Dean John N. Cobb, of the University of Washington, furnished drawings of one of the electric "stops" used in irrigation canals in Washington. H. B. Holmes, biologist with the United States Bureau of Fisheries, gave much valuable counsel and had great interest in the entire investigation. The Pacific Power & Light Co. financed the work.

PROBLEMS INVESTIGATED

The following problems were studied during the course of the experimental work at Bonneville, Oreg.:

1. What uniform voltage gradient in water will cause a fish to become paralyzed, and how does this voltage gradient vary with the length of the fish?

2. How does the voltage gradient and duration of application affect the mortality of fish subjected to excessive voltage gradients?

3. Do fish subjected to electric shocks in various degrees suffer any after effects other than those immediately observable?

4. What influence does the resistivity of the water in which the fish are immersed have upon the voltage gradient required to produce paralysis?

5. What variation in water resistivity is found in various rivers and streams?

6. Do fish, when swimming into an electrified area, such as that around an electric screen, sense the direction of the danger?

7. Does the relation of the lines of electric-current flow and the equipotential surfaces with respect to the opening protected and the direction of water flow in the stream have any influence on the effectiveness of an electric screen?

8. Will an electric screen effectively prevent fish entering a protected area?

EXPERIMENTAL DATA

VOLTAGE GRADIENT REQUIRED TO PRODUCE PARALYSIS

One of the most fundamental things needed to be known in connection with the application of electricity to fish screens was the order of magnitude of the voltage gradient required to produce paralysis and cause fish to lose all control of movement. To obtain these data, an aquarium with glass sides and wood bottom and ends was fitted with two parallel metal plates having as nearly as practical the same area as the cross section of the aquarium. These plates were connected with the secondary

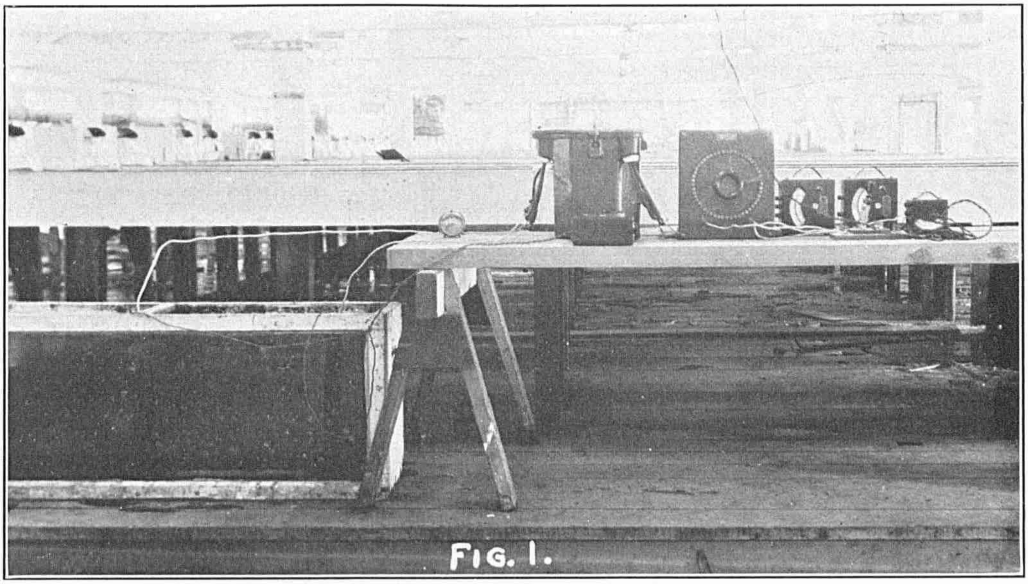

FIG. 1.—Apparatus for uniform voltage gradient tests

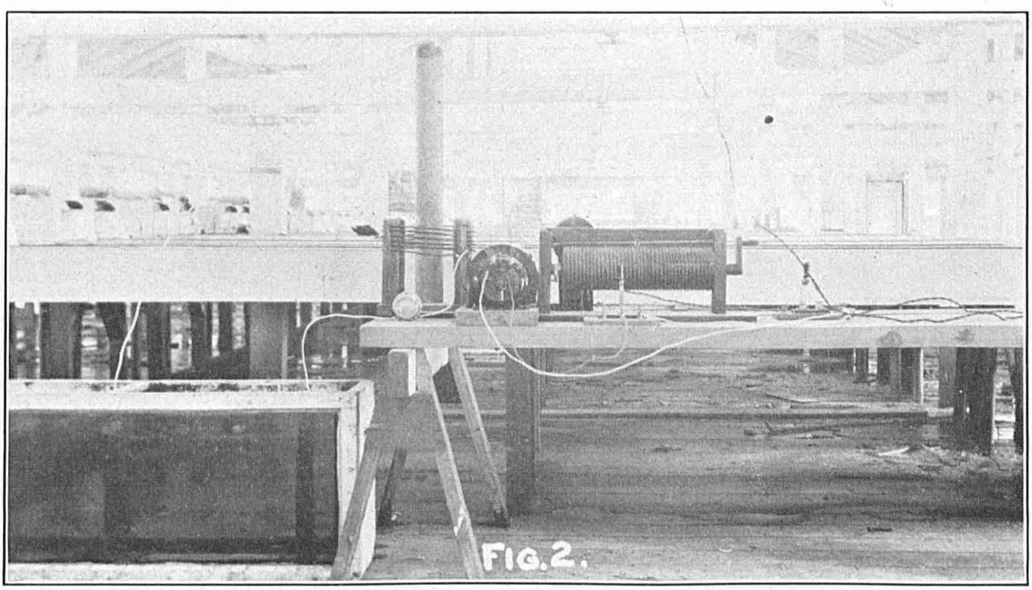

FIG. 2.—High-frequency apparatus

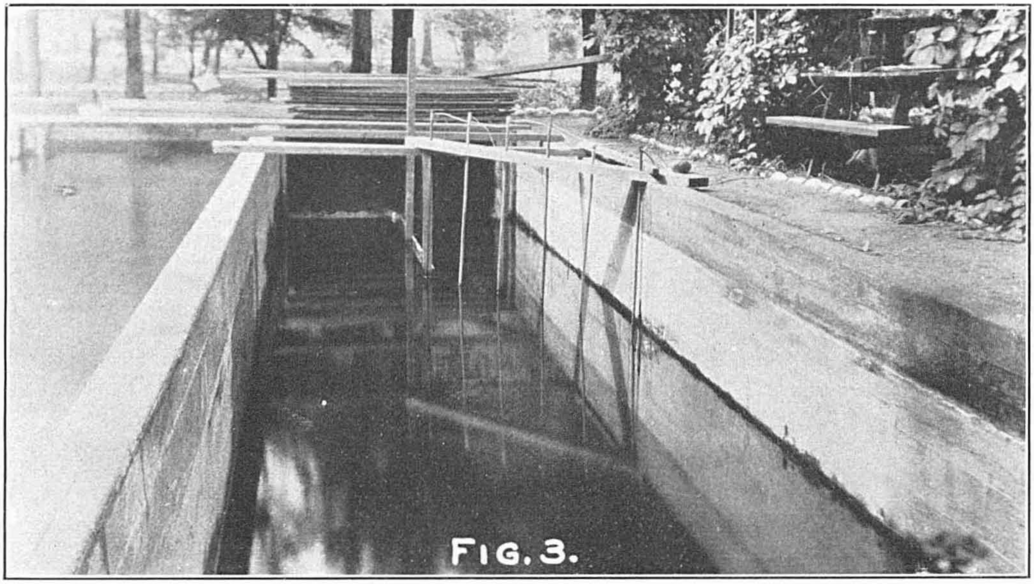

Fig. 3.—Electric screen in concrete pool

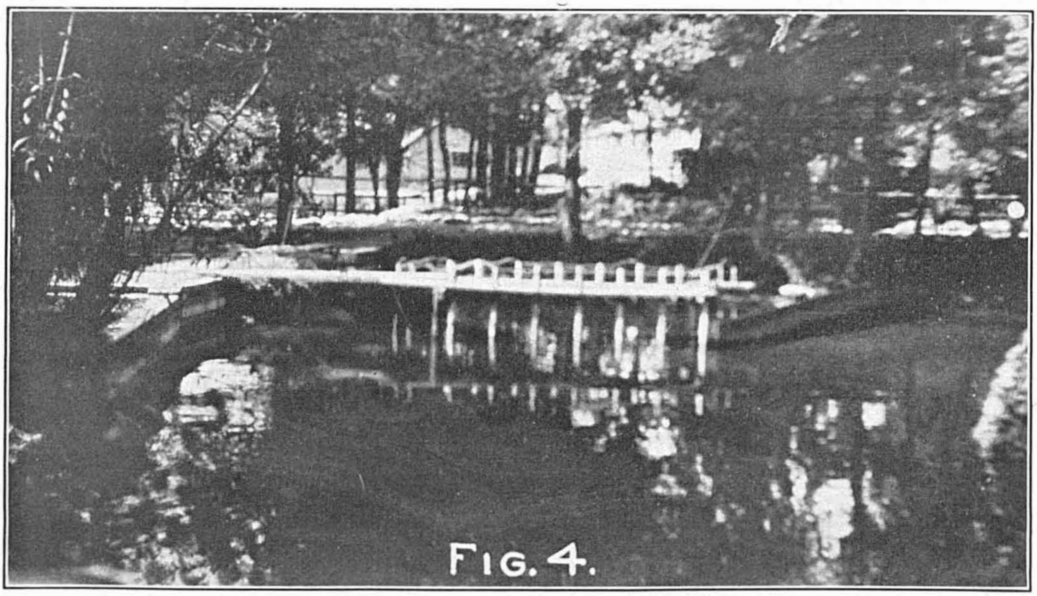

Fig. 4.—Electric screen in pond number 12

terminals of an insulating transformer. The insulating transformer was used to insure against leakage to ground from one plate, due to the grounded neutral of the 110–220 volt lighting circuit. A variable voltage from zero to the maximum value required was obtained by the use of a resistance potentiometer supplying the primary of the insulating transformer. A picture of this apparatus as set up is shown in Figure 1. This arrangement of parallel plates supplied from a variable voltage supply makes it possible to obtain a uniform voltage gradient in the aquarium of any desired value from zero to the maximum necessary in these experiments. All of the tests described in this report, unless otherwise specified, were made with 60-cycle alternating current. The voltages and the voltage gradients are root mean square values.

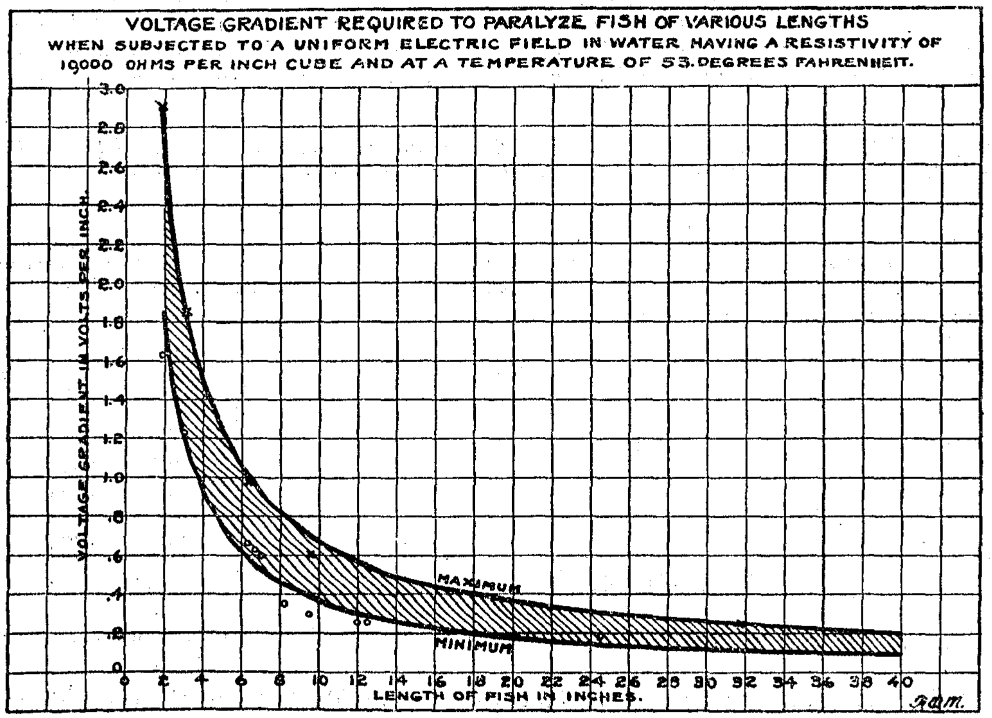

FIG. 5

The method of determining the paralysis voltage was to place a number of fish selected for uniformity of size in the aquarium between the parallel plates and raise the voltage in small increments, holding each increment one minute. When the first fish became paralyzed the plate voltage was recorded as the minimum paralysis voltage. The increase in voltage was continued until the fish were paralyzed and the plate voltage again recorded, this time as the maximum paralysis voltage. From these voltages and the known plate spacing the minimum and maximum voltage gradients per inch to produce paralysis were calculated. The lengths of the fish used in the experiment were measured carefully then from the tip of the snout to the end of the middle rays of the caudal (tail) fin. These measurements were made in inches. The average length of the test group was calculated and recorded. These tests were repeated on many fish ranging in length from 1.87 to 31.75 inches. A summary of the results is tabulated in Table 1, tests 1 to 14, inclusive, and shown graphically in Figure 5. These data bring out two very interesting facts. First, the voltage gradient required to produce paralysis is very low. Second, the voltage gradient required to produce paralysis is inversely proportional to the length of the fish. In other words, the long fish require a much lower field strength to paralyze them than the short ones. This is the opposite of the conception held by many previous to these tests. In fact, the most recent patent found covering an electric fish "stop" makes the following statement (Burkey, 1924):

> With the use of the transformer it is possible to have an electric current at the inlet end of the fish "stop" of a low amperage for the purpose of stopping or turning back small fish and thereby obviate any possible chance of injuring or killing small fish by coming in contact with electrical current of too high amperage. The electrodes, being arranged in three series and connected to the transformer, permit electrical currents to be passed through the water of progressively increasing amperage, so that when large fish are not stopped or turned back by the low amperage the intermediate series of electrodes will supply electrical current of sufficient amperage to turn back or stop such sized fish.

TABLE 1.—*Voltage gradient required to paralyze fish of various lengths when subjected to a uniform electric field in water having a resistivity of 10,000 ohms per inch cube and at a temperature of 53° F.*

Test No.	Fish			Voltage gradient, in volts per inch, to paralyze the fish	
	Species	Number	Length		
			Inches	*Minimum*	*Maximum*
1	Rainbow and loch leven	30	1.87	1.630	2.910
2	Chinook	30	3.10	1.230	1.850
3	Rainbow	3	6.25		.975
4	do	3	6.29	.666	
5	do	3	6.67	.625	
6	do	1	7.00	.596	
7	do	1	8.25	.358	
8	do	1	9.50	.296	
9	do	1	9.50		.592
10	do	1	12.00	.250	
11	do	1	12.50	.292	
12	do	1	12.50	.250	
13	Chinook, male	1	24.50	.188	
14	Chinook, female	1	31.75		.250

NOTE.—The rainbow trout were *Salmo irideus;* the loch leven trout were *Salmo levensis;* and the Chinook salmon were *Oncorhynchus tschawytscha.*

It is obvious, in the light of the facts as given by Table 1 and Figure 5, that the situation is just the reverse of that anticipated by the fish-stop inventor quoted above.

The equation for the "minimum" length-voltage gradient for paralysis curve has been calculated and found to be

$$g=3.70L^{-0.99}$$

which, within permissible limits of error, may be written

$$g=\frac{3.70}{L}$$

where g = voltage gradient per inch to produce paralysis and L = length of fish in inches.

Thus it is seen that there is a very simple and interesting relation between the length of fish and the voltage gradient required to produce paralysis. This equation applies for water having a resistivity of 10,000 ohms per inch cube, but for other resistivities the constant term 3.70 must be modified, as will be shown later under the discussion of the influence of water resistivity upon paralysis-voltage gradient.

It has been suggested that different species of fish may require different voltage gradients to produce paralysis. This point should be investigated further. Tests were made on four different species at Bonneville, and all gave results that fell within the range between the minimum and maximum curves. It is probable that no greater variation will be found between the different species involved in protection problems than is found between individuals of the same species. That there is considerable variation between individuals is shown by the separation of the maximum and minimum curves of Figure 5. This variation is due to several factors, among which may be mentioned slight variation in the length of individuals in a test group, variation in the condition and vitality of individuals and the position of the fish with respect to the lines of current flow, and the equipotential surfaces in the electric field. Great care was exercised to obtain healthy, normal fish. Some of the rainbow trout at Bonneville were found to be infested with an external copepod parasite, which attacks the mouth and gills. For this reason all of the rainbow trout used were examined carefully for this parasite, and those infested to a degree that would affect their vitality were rejected.

HIGH-FREQUENCY TEST

A high-frequency oscillator was set up, as shown in Figure 2, and a group of 30 chinook-salmon fingerlings, averaging 3.04 inches in length, was subjected to a 500,000-cycle electric field. Plate voltages more than 100 times those used at 60 cycles were applied. None of the fish gave any indication of feeling the existence of an electric field in the water. This phenomenon probably is due to the fact that virtually all of the current at this high frequency is flowing on the surface of the water between the electrodes, and consequently there is no appreciable electric field in the water.

CONTINUOUS-CURRENT TEST

A continuous-current test was made on a group of 30 chinook-salmon fingerlings, using the direct-current exciter in the hatchery hydraulic-power plant as a source of continuous potential. The voltage gradients for paralysis were 1.33 volts per inch minimum and 2.0 maximum. The average length of the fish was 3.0 inches. These values check the 60-cycle alternating-current tests very well, as shown by the maximum and minimum curves in Figure 5.

DURATION OF APPLICATION AND MORTALITY

Returning to the 60-cycle alternating-current source of supply, a series of tests was made to determine the influence of the time of voltage application on the number of fish killed. These tests were made on chinook-salmon fingerlings having an average length of 3.1 inches. They were made by subjecting 14 groups of approximately 30 fish each to a definite voltage gradient for a fixed period of time. The voltage gradients were selected from below the paralysis value to values of approximately twice this voltage gradient, and two arbitrary periods of application (1 minute and 5 minutes) were chosen. An entirely fresh lot of fish was used for each test to eliminate any cumulative effects from repeated voltage applications. The results of these tests

110928—28——2

are summarized in Table 2. These data show conclusively, as one would expect, that the duration of application of the potential has a decided effect upon the mortality of the fish when voltage gradients above the paralysis value are applied. A voltage gradient of 1.48 volts per inch, used in test No. 19, paralyzed 26 of the 30 fish in one minute but did not kill any of them. Essentially the same voltage gradient, 1.46 volts per inch, used in test No. 27, paralyzed all of the fish, and after a 5-minute application 69 per cent of the fish did not recover. The duration of the period of complete paralysis or suspended animation appeared in every case to be the greatest factor in determining recovery from electric shock. Virtually, without exception, it was observed that when a group of fish was paralyzed the recovery was in the inverse order of the paralysis—that is, the fish paralyzed first were last to recover and those paralyzed last were first to recover.

TABLE 2.—*Influence of voltage gradient and duration of application on mortality of chinook-salmon fingerlings 3.1 inches long when subjected to a uniform electric field in water having a resistivity of 10,000 ohms per inch cube and at a temperature of 53° F. Electrode plates, 212 square inches area, spaced 12 inches apart*

Test No.	Number of fish	Plate voltage	Voltage gradient, volts per inch	Duration of application, minutes	Fish killed	
					Number	Per cent
17	30	14.4	1.20	1	0	0
18	27	16.0	1.33	1	0	0
19	30	17.8	1.48	1	0	0
20	30	19.9	1.66	1	3	10
21	30	22.2	1.85	1	3	10
22	31	24.5	2.04	1	12	38.7
23	30	29.7	2.48	1	17	56.6
24	30	5.57	.464	5	0	0
25	30	10.25	.854	5	0	0
26	30	15.0	1.25	5	0	0
27	29	17.5	1.46	5	20	69
28	29	20.4	1.70	5	18	62
29	30	23.0	1.92	5	20	66.6
30	29	25.5	2.12	5	23	79.3

OBSERVATIONS DURING PARALYSIS AND RECOVERY

Some interesting observations were made of the characteristic behavior of fish during the application of potential and during the recovery from an electric shock. These will be given here. When the electrode voltage is increased gradually from a very small value the fish begin to show signs of feeling the potential at from 10 to 20 per cent of the value for paralysis. This is indicated by short, quick, caudal (tail) fin movements and slight shifts in position. At from 50 to 80 per cent of the paralysis voltage they become quite active, swimming about in all directions, seeking to avoid the uncomfortable electric field. Just before reaching the paralysis voltage, the fish are extremely active, dashing about trying to escape the field. Then they become paralyzed, the pectoral fins stand motionless and virtually at right angles with the body; the fish then turns belly up and sinks to the bottom, where it lies on one side. In some instances the gill action apparently stops entirely, while in others it continues feebly. The entire fish turns perceptibly lighter in color while paralyzed. The change in color is due to changes in the distribution of the pigment in the chromatophores of the skin (Kuntz, 1917). These chromatophores are probably under the direct control of the sympathetic nervous system and hence are disturbed very seriously by a severe electric shock. The first indication of recovery after the potential is removed is a reestablishment of gill action, or a strengthening of it if the gill action has not stopped entirely. After the gill action has reached nearly normal the body begins to flex, and in a short time the normal swimming position is resumed.

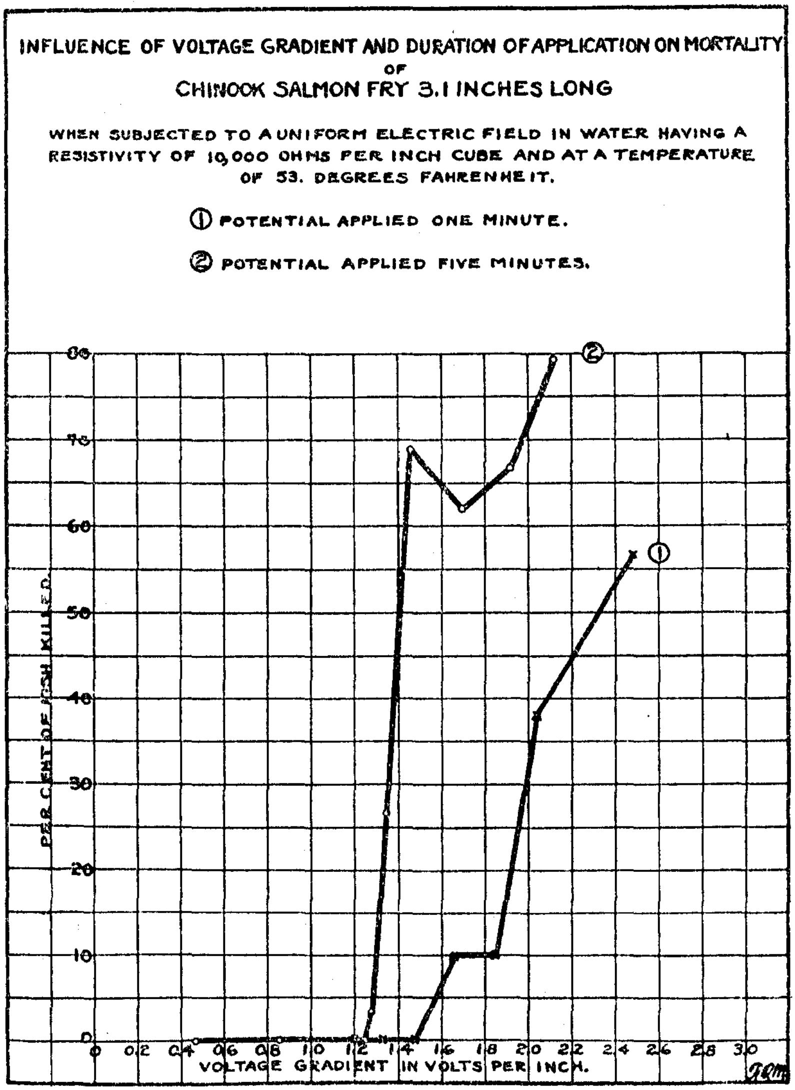

FIG. 6

The movements are slow and sluggish at first, but, except in the most severe cases, normal activity is resumed quickly. This recovery from electric shock requires varying amounts of time from a few seconds to 45 or more minutes. The longest time of recovery accurately recorded during the tests was 45 minutes for a 7-inch rainbow trout.

OBSERVATIONS AFTER ELECTRICAL TESTS

All of the fish used in tests 1 to 30, inclusive, except those killed outright, were kept, segregated by test numbers, in the running water of the hatchery troughs for observation. Check groups taken from the same hatchery pools, which had not been subjected to any potential, were used for comparison. These fish, totaling 407 in number, were observed very carefully twice daily for 10 days. During this period the fish that had been subjected to the electrical tests did not develop a single symptom that did not develop in the check groups as well. During the first two days of observation one fish that had been subjected to a high-voltage gradient became

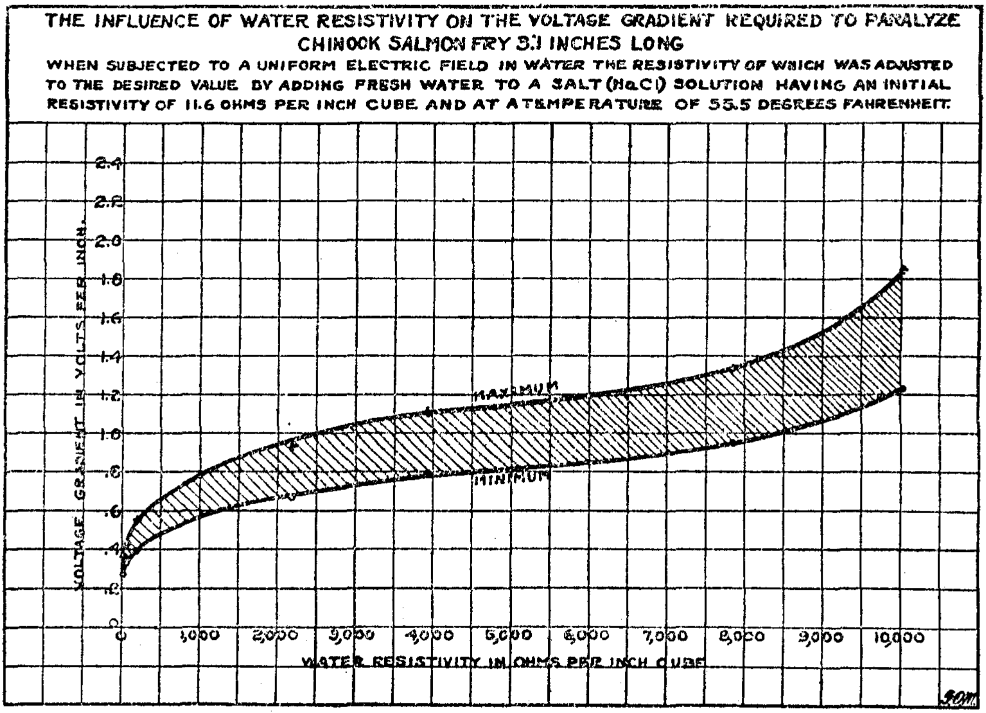

FIG. 7

blind, and it was thought at first that it was due to an electrical injury. Later, however, fish in the check groups became blind in the same manner. During the observation period 9 of the 407 fish became blind in one eye. This blindness probably was caused by mechanical injury in the close confinement of the hatchery troughs. The male and female chinook salmon used in tests 13 and 14 of Table 1 were taken from a group of 21 being held in one of the ponds on Tanner Creek for spawning purposes. These salmon had scars by which they could be identified, and after reviving from an electrical test they were returned to the pond. These fish spawned later, and Eugene Howell, the superintendent of the hatchery, reported that milt and eggs were normal and did not show any evidence of sterilization.

INFLUENCE OF WATER RESISTIVITY ON THE PARALYSIS-VOLTAGE GRADIENT

A series of paralysis-voltage gradient tests were made with chinook-salmon fingerlings, using water varying in resistivity from 11.6 to 10,030 ohms per inch cube to determine the influence of water resistivity upon the paralysis-voltage gradient. The results of these tests (Nos. 31 to 37, inclusive) are summarized in Table 3 and shown graphically in Figure 7. The water resistivity was adjusted to the desired value in these tests by first making a salt (NaCl) water solution that had the resistivity of sea water; fresh water was then added to obtain the desired increments in resistivity. These data show a rapid change in the voltage gradient required to paralyze fish at low values of water resistivity, a slower change at intermediate resistivities, and a rapid change again at high resistivities. The range of resistivities covered by this investigation, it should be noted, is from sea water to high-resistivity mountain-stream water, and in this range the minimum paralysis-voltage gradient changes from 0.27 to 1.23 volts per inch, or 4.55 times. It is necessary then to introduce a water-resistivity correction factor in the previous equation. It may now be written

$$g = \frac{3.70\ W}{L}$$

where g = voltage gradient per inch to produce paralysis, L = length of fish in inches, and W = correction factor for water resistivity. (See Table 4 for values of W for different water resistivities from 10 to 10,000 ohms per inch cube.)

TABLE 3.—*Influence of water resistivity on the voltage gradient required to paralyze chinook-salmon fingerlings 3.1 inches long when subjected to a uniform electric field in water, the resistivity of which was adjusted to the desired value by adding fresh water to a salt (NaCl) solution having an initial resistivity of 11.6 ohms per inch cube and at a temperature of 55.5° F.*

Test No.	Number of fish	Water resistivity, ohms per inch cube	Voltage gradient, in volts per inch for paralysis	
			Minimum	Maximum
31	30	11.6	0.271	0.366
32	30	53.2	.333	.423
33	30	194.0	.396	.560
34	30	2,180.0	.666	.937
35	30	3,930.0	.791	1.110
36	30	7,850.0	.950	1.339
37	30	10,030.0	1.230	1.850

TABLE 4.—*Correction factor, "W," for various water resistivities for the minimum voltage-gradient equation* $g = \frac{3.70W}{L}$

Water resistivity, ohms per inch cube "ρ"	Correction factor for water resistivity "W"	Water resistivity, ohms per inch cube "ρ"	Correction factor for water resistivity "W"
10	0.210	3,000	0.612
50	.268	4,000	.654
100	.297	5,000	.679
200	.335	6,000	.712
300	.365	7,000	.755
500	.402	8,000	.805
1,000	.477	9,000	.897
2,000	.561	10,000	1.000

WATER RESISTIVITY OF VARIOUS STREAMS

The resistivity of the water has such an important influence upon the voltage gradients and voltages that should be used on electric fish screens that it is very important to know something of the variation in resistivity found in various streams.

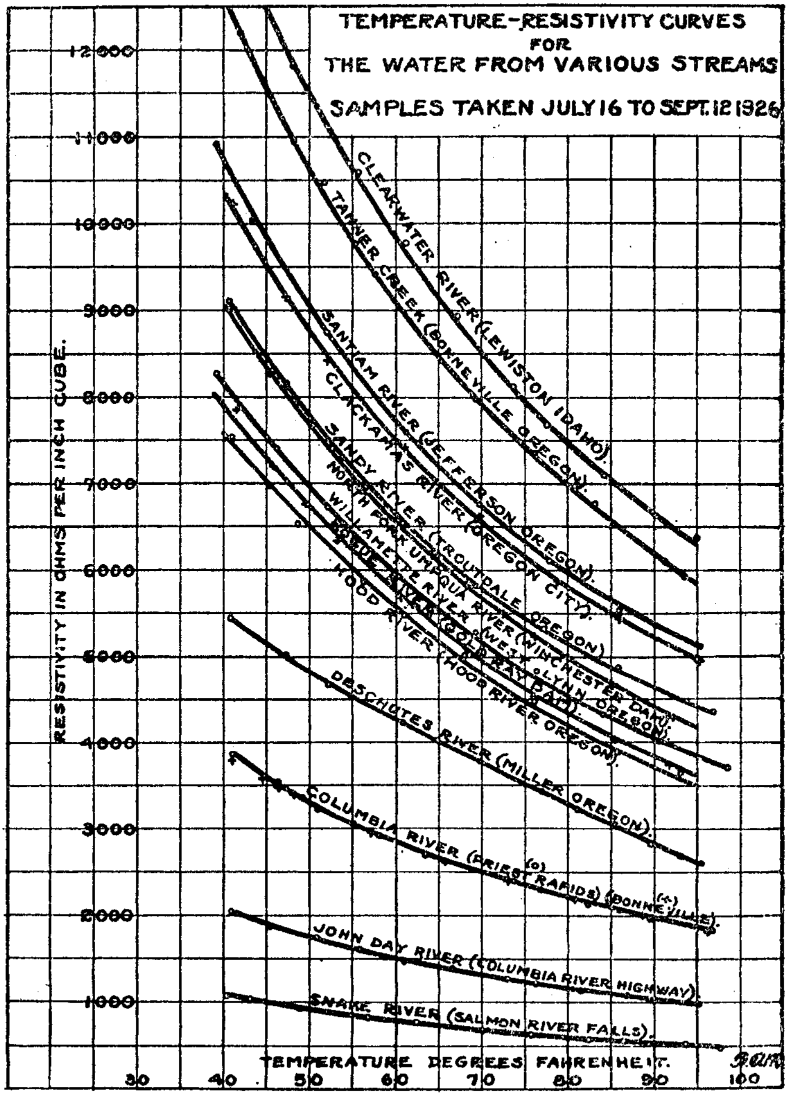

FIG. 8

To obtain this information, samples of water were secured from 12 rivers, 1 creek, and the Pacific Ocean.

Temperature-resistivity data were taken for each of these samples by chilling the water to approximately 40° F., then measuring the resistivity as the sample was warmed in increments to approximately 95° F. All water resistivities used in this investigation were measured by the Kohlrausch U-tube method, using a double commutator with the resistance bridge to insure the elimination of all polarization effects (Kohlrausch, 1883). These temperature-resistivity data for the various streams are plotted with rectangular coordinates in Figure 8. An examination of these curves shows that there is a great variation in the resistivity of the water from various streams. The Snake River water, for example, has a resistivity of 800 ohms per inch cube at 60° F., while the Clearwater River water has a resistivity of 9,850 ohms,

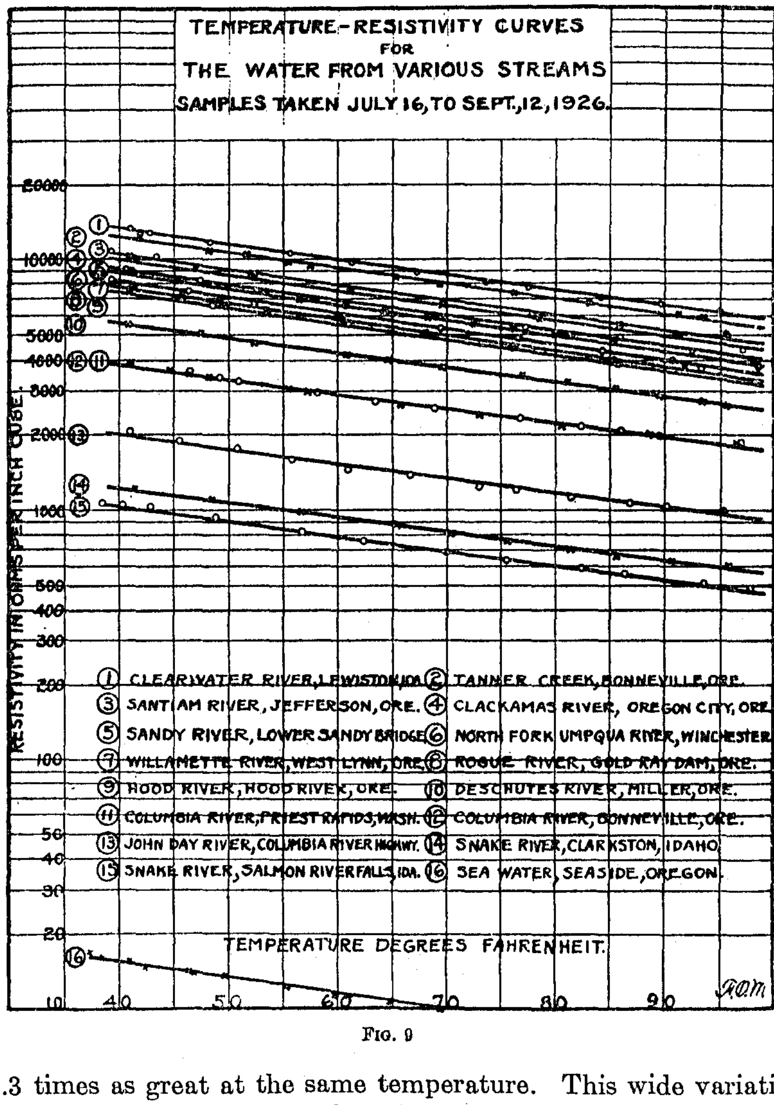

FIG. 9

which is 12.3 times as great at the same temperature. This wide variation in resistivity is due, of course, to dissolved salts taken up by the water in the stream and its tributary drainage basin. An inspection of these curves shows that all of the streams having low-resistivity water rise east of the Cascade Mountains and pass through semiarid alkali sections. The Clearwater River rises in the Bitter Root Mountains of Idaho. The other streams rise in the Cascade Mountains and are fed, in general, by melting snow and glaciers, with the result that they are grouped fairly close together in water resistivity and the value is relatively high.

The resistivity of the sea-water sample from Seaside, Oreg., was so low that it could not be plotted in Figure 8. The resistivity of the sea water at 60° F. was 11.2 ohms per inch cube, or 1/880 that of the Clearwater River water at the same temperature.

Figure 9, a semilogarithmic plot of these temperature-resistivity data for the waters from all of the sources investigated, shows two very interesting relations. First, all of the curves are straight lines; second, all of the curves are parallel. The significance of all of the curves being straight lines when plotted this way is that the temperature-resistivity characteristic within the limits of temperature investigated can be represented by an exponential equation of the form

$$\rho = A\epsilon^{-b\Theta}$$

where ρ = the resistivity in ohms per inch cube, Θ = the temperature in degrees Fahrenheit, $\epsilon = 2.7183$ base of Naperian logarithms, A = a constant, and b = a constant.

The significance of all of the curves being parallel is that the slopes are all the same; therefore, the constant term b in the exponent of this equation is the same for sea water and the water from every stream investigated. The numerical value of the constant b was calculated and found to be 0.014. The values of the constants A for the various kinds of water were calculated and are tabulated in Table 5. With these values of the constant term A and 0.014 for the constant term b in the above equation, the resistivity of any of the waters investigated can be calculated for any temperature from 40 to 100° F., with a maximum error not greater than 3 per cent. Therefore, the temperature-resistivity characteristics for the waters studied can be represented over the range of temperature from 40 to 100° F. by the following equation:

$$\rho = A\epsilon^{-0.014\Theta}$$

where A is a constant having a different value for the water from each stream and for the waters investigated has a minimum value of 26.9 and a maximum value of 23,100.

TABLE 5.—*Constants for water temperature-resistivity equation* $\rho = A\epsilon^{-b\Theta}$

Stream	Location at which sample was taken	Constant A	Constant b
Sea water (Pacific Ocean)	Seaside, Oreg.	26.9	0.014
Snake River	Salmon River Falls, Idaho	1,840.0	.014
Do	Clarkston, Idaho	2,240.0	.014
John Day River	Columbia River Highway, Oreg.	3,630.0	.014
Columbia River	Bonneville, Oreg.	6,850.0	.014
Do	Priest Rapids, Wash.	6,850.0	.014
Deschutes River	Miller, Oreg.	10,000.0	.014
Hood River	Hood River, Oreg.	12,970.0	.014
Rogue River	Gold Ray Dam, Oreg.	13,500.0	.014
Willamette River	West Lynn, Oreg.	14,130.0	.014
North Fork Umpqua River	Winchester, Oreg.	15,500.0	.014
Sandy River	Lower Sandy Bridge, Oreg.	15,850.0	.014
Clackamas River	Oregon City, Oreg.	17,800.0	.014
Santiam River	Jefferson, Oreg.	18,400.0	.014
Tanner Creek	Bonneville, Oreg.	21,630.0	.014
Clearwater River	Lewiston, Idaho	23,100.0	.014

Seasonal variations will occur in the resistivity of the water in a stream. In some streams this variation will undoubtedly be much larger than in others. One stream that has been investigated has a seasonal variation in resistivity of 13 per cent at a constant reference temperature. The maximum resistivity occurs during the period of maximum run-off. Fortunately, electric fish screens do not need to be designed within very close limits, and no trouble is anticipated from variations in the water resistivity of a stream.

DO FISH SENSE THE SOURCE OF AN ELECTRIC FIELD AND AVOID IT?

Another fundamental fact that must be known is whether or not fish, swimming into an electrified area, sense the direction of danger. In an effort to determine this point several tests were made in the outside pools at the Bonneville hatchery. The first four tests were made in a rectangular concrete pool 8 feet wide, 4 feet deep, and 48 feet long, including the spillway. Twelve feet of the lower end of this pool next to the spillway were divided into two 4-foot channels by a tight partition of 1 by 12 inch boards. Facing downstream, the right-hand channel was selected to be protected by the electric screen. The arrangement of this pool and the second screen used are shown in Figure 3.

The first screen was made of four ½-inch standard-pipe electrodes spaced 18 inches apart and in a single row, making an angle of 60 degrees in the direction of stream flow. Alternate electrodes were connected and made the same electrical polarity; this arrangement made adjacent electrodes opposite in polarity. About 200 chinook-salmon fingerlings 10 months old were liberated at the upper end of the pool. When undisturbed they avoided the electrified area around the screen fairly well, but when frightened they would swim through it into the protected channel. This screen was defective in three ways, as will be shown later in the discussion of the proper relation of the lines of current flow and equipotential surfaces with respect to the direction of water flow and the plane of the protected opening and the proper size of electrodes. First, the lines of electric-current flow were in the wrong direction with respect to the water flow; second, they were in the wrong direction with respect to the protected opening; and third, the electrodes were too small in diameter.

The second screen test was made in the same pool, and all of the conditions were kept the same, except that the number of electrodes was increased to six and the angle of the line of electrodes with the direction of water flow was reduced from 60 to 30 degrees. Approximately 2,000 chinook-salmon fingerlings 10 months old were liberated in the open end of the pool and observed. They seemed to avoid the screen fairly well, although some would swim through into the protected channel. At 4.30 p. m. the protected area was cleared of fish and 30 volts left on the electrodes for the night. The next morning at 8 o'clock 50 fingerlings were in the protected area and 6 had been electrocuted during the 15.5 hours the screen had been on. The fish were then driven back and forth past the screen, and they avoided the electrified area fairly well but would dash through at times. This screen was still defective in regard to the size of the electrodes. The direction of the lines of current flow, however, had been improved by making them more nearly parallel with the direction of stream flow and more nearly perpendicular to the plane of the protected opening. Leaving all conditions except the screen as they were before, a third screen was constructed,

110928—28——3

consisting of two parallel rows of ½-inch standard pipe spaced 18 inches apart in the rows and the two rows 2 feet apart. The angle of the electrode rows with the direction of stream flow was kept at 30 degrees, as before. The electrodes of each row were connected parallel and the two rows made opposite in polarity. This arrangement of electrodes put the lines of current flow approximately in the direction of stream flow, and consequently in the direction the fish approach the screen. With some trout used in the previous test in the open channel, the electrodes were energized with 24.5 volts and left on from 4.30 p. m. until 8 a. m. The fish did not enter the protected channel. It was observed that trout that had passed through the electric field of the screen could not be driven through it again except with great difficulty. For this reason a new group of 12 rainbow trout was substituted for those that apparently had become screen shy. When first liberated, 5 of the 12 were frightened and dashed through the screen. They were then driven out into the open end of the pool and the potential left on over night. The fish did not reenter the screened area during the night, and the next morning we were unable to drive any of them through the screen.

The fourth screen used was but a very slight modification of the third. One electrode was added to fill a rather large opening on the by-pass channel side of the screen. The electrode voltage was adjusted to 23 volts, and approximately 2,500 chinook-salmon fingerlings were put in the outside channel at 11.30 a. m. These fish were allowed to move about as they pleased. Frequently the entire school would swim directly toward the screen but always turned away when within from 18 to 24 inches of the first row of electrodes. They were continually feeding on elm beetles, which were blown on the water from the elm trees above the pool, but they would never venture through the screen for those in the protected area. An attempt was then made to attract them through the screen by throwing a mixture of ground salmon and salmon eggs between the electrodes and in the protected area. They could be drawn into the screen by throwing the food outside and leading up to it, but they would dash out without taking the food and never passed beyond the second row of electrodes. The only way the young salmon could be driven through the screen was by fright. A few were driven through the screen by waiting until a school was immediately in front of the screen and then making a sudden motion toward them with a pole, net, or other device.

The last two screens tried were by far the most effective. This undoubtedly was due to a more effective use of the electric field by arranging the lines of current flow parallel with the stream flow and at right angles with that of the protected opening. The tests in the concrete pool, however, were not as conclusive as they might have been, because conditions were unnatural. The water velocity was extremely low; in fact, it was virtually still water, hence the fish did not line up with the direction of water flow as in a stream. The pool was near the main hatchery driveway, and the fish were continually frightened and disturbed by tourists and therefore were unnatural in their behavior. However, those who witnessed the tests with the third and fourth screens were convinced that the fish did have a directional sense of the location of the source of the electric fields and a decided inclination to avoid them. These observations led to the decision to install a screen under more natural and normal conditions for further observations and tests. This screen and the results obtained will be discussed later in this report.

DIRECTION OF THE ELECTRIC FIELD WITH RESPECT TO THE PROTECTED OPENING AND THE STREAM FLOW

The experience with the four electric screens tested in the concrete pool and the tests conducted in the aquarium demonstrated clearly the importance of considering the direction of the lines of current flow and the equipotential surfaces in the water. The lines of current flow and the equipotential surfaces for two parallel gratings of opposite polarity and consisting of parallel cylindrical electrodes immersed in water or any electrolyte of uniform resistivity are shown by Figure 10. The lines of current flow originate in one electrode and terminate in the one of opposite polarity. The lines of current flow in Figure 10 are drawn to include one-thirty-sixth of the current from one electrode between adjacent lines of current flow. The equipotential surfaces start as eccentric circular tubes about the electrodes, change to elliptical tubes, then to curved surfaces passing in front of the electrodes along the plane of the grating, gradually straightening out into a plane surface midway between the gratings. Figure 10 is drawn as a plane surface at right angles to these equipotential surfaces, hence they appear as lines in the drawing. These equipotential surfaces are drawn so that one-fortieth of the potential between the gratings is included between adjacent equipotential surfaces. Such a graph is very helpful in the study of the electric field between gratings, because the distance between the lines of current flow is a measure of the current density, and the distance between the equipotential surfaces is a measure of the rate of change of potential or voltage gradient. The nearer the lines of current flow are together the greater the current density, and the nearer the equipotential surfaces are together the higher the voltage gradient.

It should be noted that the lines of current flow and the equipotential surfaces always intersect at right angles. The equipotential surfaces, as the name indicates, are surfaces in which there is no change in potential. It is obvious, then, that a fish swimming in electrified water parallel with the equipotential surfaces is subjected to a potential difference only equal to that spanned by the thickness of his body, and the current that flows through his body is from side to side at right angles with the spinal column and major nerve channel. On the other hand, a fish swimming in electrified water at right angles with the equipotential surfaces and parallel with the lines of current flow is subjected to a potential difference equal to that spanned from the tip of his snout to the end of his tail, and the direction of current flow is lengthwise through the body in the direction of the spinal column and major nerve channel. The ratio of the length to the thickness of a fish is very large for most species. Then, in consideration of what has been said about the two positions of a fish in an electric field, it is obvious that when at right angles with the equipotential surfaces and parallel with the lines of current flow he will be subjected to a potential difference several times that when he is at right angles to this position. Furthermore, in this position the direction of current flow is in the direction of the spinal column and main nerve channel and is probably much more effective in producing a disagreeable sensation.

In all of the tests when moderate values of potential were used (so the fish were not in too great distress) there was always a decided tendency to line up with the equipotential surfaces. This is, of course, the most comfortable position if there is no way to escape from the field entirely.

The above observations show the necessity, when using an electric screen for protecting an opening, of having the equipotential surfaces parallel with the plane of the opening and the lines of electric-current flow perpendicular to this plane.

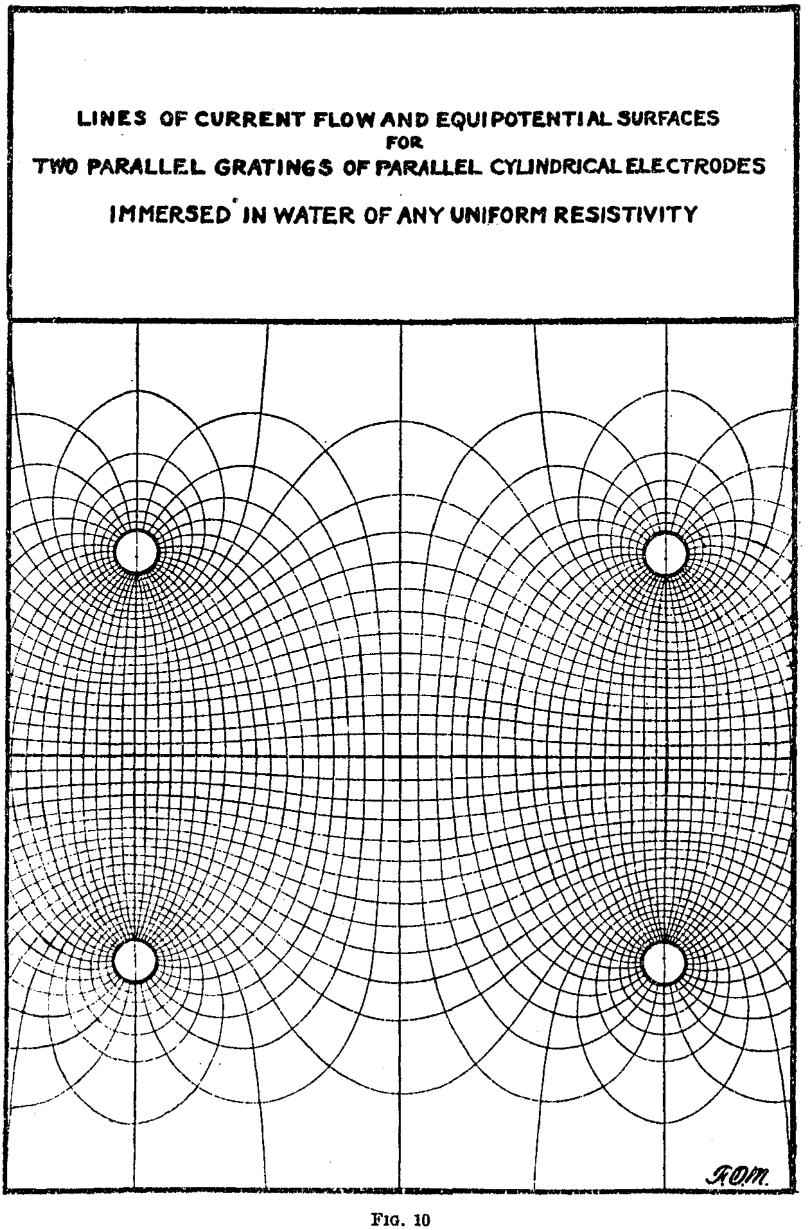

FIG. 10

When in swift water fish hold their bodies parallel with the direction of stream flow for ease in swimming. This fact must also be taken account of when installing an electric screen. The lines of electric-current flow must be parallel with the direction of water flow and the equipotential surfaces at right angles to the direction of water flow.

When an electric screen is installed in such a way that the field has the correct relation to both the opening protected and the direction of water flow, as explained above, fish entering the electric field of the screen are almost compelled to enter parallel with the lines of current flow and at right angles to the equipotential surfaces. This is the position of maximum discomfort and hence is most effective in discouraging further progress toward the protected opening.

Heretofore no attention has been given to the relation of the electric field to the protected opening and to the direction of stream flow. As far as is known, all of the electric "stops" have been installed, either with a plate (or metal screen) on each side of the protected opening (these plates being of opposite polarity), or several electrodes have been used in one or several rows across the opening, the electrodes in the rows alternating in polarity. Both of these schemes, it will be observed, produce an electric field in which the lines of current flow are parallel with the plane of the opening and the equipotential surfaces are perpendicular to this plane. This arrangement, as shown above, is the most ineffective that it is possible to make, and if any success has been attained at all by this arrangement it augurs well for electric screens installed with the field in the proper relation to the opening and water flow.

ELECTRIC SCREENS SHOULD BE USED AS DEFLECTORS, NOT STOPS

Another serious error that has been made in the installation of electric "stops" has been the attempt to use them as impenetrable barriers in canals, sometimes miles from the intake at the supply stream. This, in general, is not good practice even if successful in stopping the fish, especially for young salmon fingerlings that are impelled by instinct to migrate downstream toward the ocean. They may be held for months by such a trap and may never return upstream to the intake and main stream leading to the ocean. A short interruption of the potential supply on an electric screen so installed would allow fish to escape past the screen, making successful screening action for months of no avail. It is recommended that electric screens, when used, be installed as deflectors, by-passing fish around the openings to artificial waterways dangerous to their well-being, always keeping the fish, as far as possible, in the natural stream channels.

LAST FISH-SCREEN TEST AT BONNEVILLE

Following the fish-screen experiments in the concrete pool, which have been described, it was decided to make an electric-screen test with more fish and under as nearly as practical natural stream conditions. After an examination of the ponds and waterways at the Bonneville hatchery it was decided that ponds Nos. 12, 15, and 16, with their interconnecting waterways, offered the best available location for the fifth and last electric-screen test made during this investigation. A map is included in this report (fig. 11), showing the arrangement of these ponds, the location of the electric screen, and the quantities of water flowing in the various interconnecting channels. The arrangement shown by the map was chosen because the application of the by-pass or deflector principle of using the electric screen could be applied readily. The water flowing through pond No. 12 into pond No. 15 and finally discharging into pond No. 16 represents the natural stream channel, and the flow from pond No. 12 through the west waterway into pond No. 16 represents the artificial waterway from which the fish were to be protected. The water flow in the two paths was adjusted to the desired value by regulating the water level in pond No. 15 with stop boards at the discharge into pond No. 16. The flow of water through the electrically screened channel purposely was made 39 per cent higher than through the open channel, because it was thought that would make protection more difficult on account of

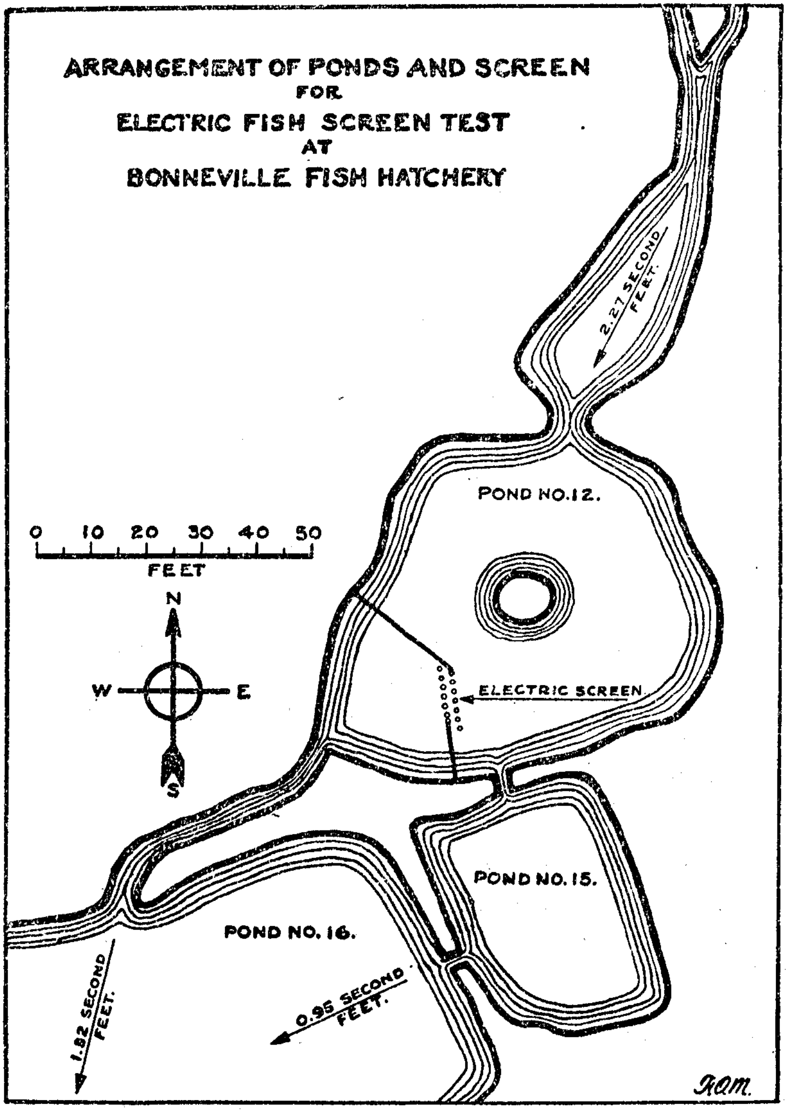

FIG. 11

the inclination of the fish to follow the maximum water flow. A wire screen was installed in the west outlet of pond No. 12 to prevent the fish that went through the electric screen into the protected area from escaping into pond No. 16. This screen made it possible to check the effectiveness of the electric screen. The 15,000 chinook-salmon fingerlings used in the experiment had been reared in pond No. 12

and therefore were normal in their activity there. The area screened was frequented by large numbers of fish before the screen was installed.

The screen installed for this test consisted of fourteen 2½-inch standard-pipe electrodes (2.875 inches outside diameter) in two rows of seven electrodes each. The electrodes were spaced 18 inches, center to center, in the rows, and the two rows were 24 inches, center to center. The electrodes of the second row were staggered 9 inches with respect to the first row, making them come opposite the centers of the openings between the electrodes of the first row. The electrodes were supported, through holes in 2 by 10 inch planks, 18 inches above the water level and projected to within 2 inches of the bottom of the pond. The electrodes in each row were connected by means of 14-gauge wire and made the same electrical polarity. The two rows of electrodes were

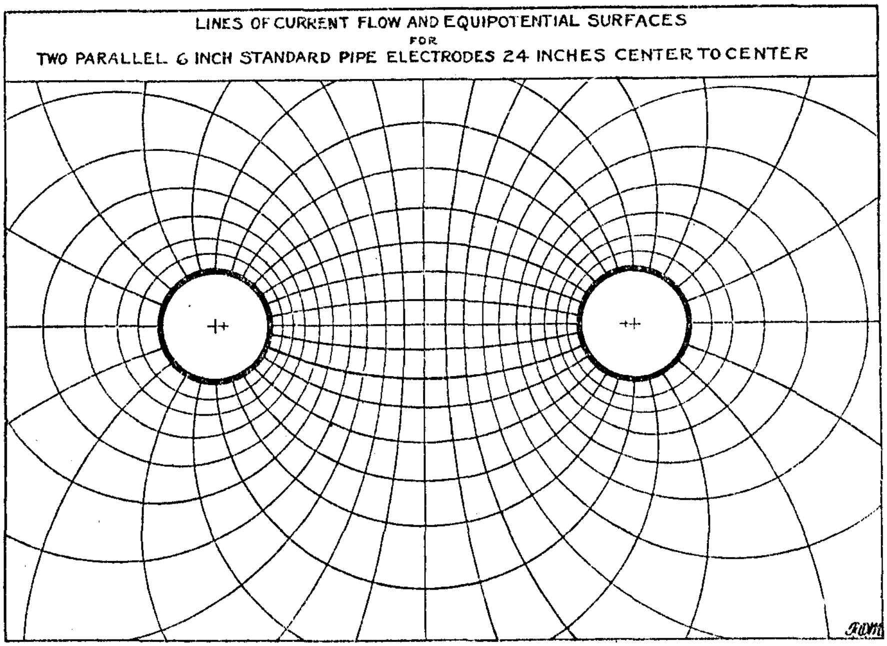

FIG. 12

of opposite polarity. The opening protected by this electric screen was 9 feet 3 inches wide.

The installation of the screen was completed at 10 a. m., August 7. The fish were attracted out of the screened area by feeding on the opposite side of the pond, and 25 volts at 60 cycles were put on the screen from a 3-kilovolt-ampere ungrounded supply transformer. A graphic recording voltmeter was connected to the potential supply to check the continuity of the electrical supply to the screen.

When the screen was first electrified the fish would drift down toward it in large schools, and as soon as the outer fringe of the school struck the electrified area it would swim out swiftly, giving warning of the danger, and the whole school would move away. The school would soon drift back into the electrified area and repeat the above movement. At times fish that drifted too far into the electrified area would become bewildered and swim through the screen. The number swimming through in this manner was very small; usually none went through; on some occasions one, two, or three; and the largest number observed to go through in six hours of observation on August 17 was six. One very interesting thing about the fish that went through the screen is that almost invariably upon finding that they were separated from the main school they would dash back through the screen to join the school.

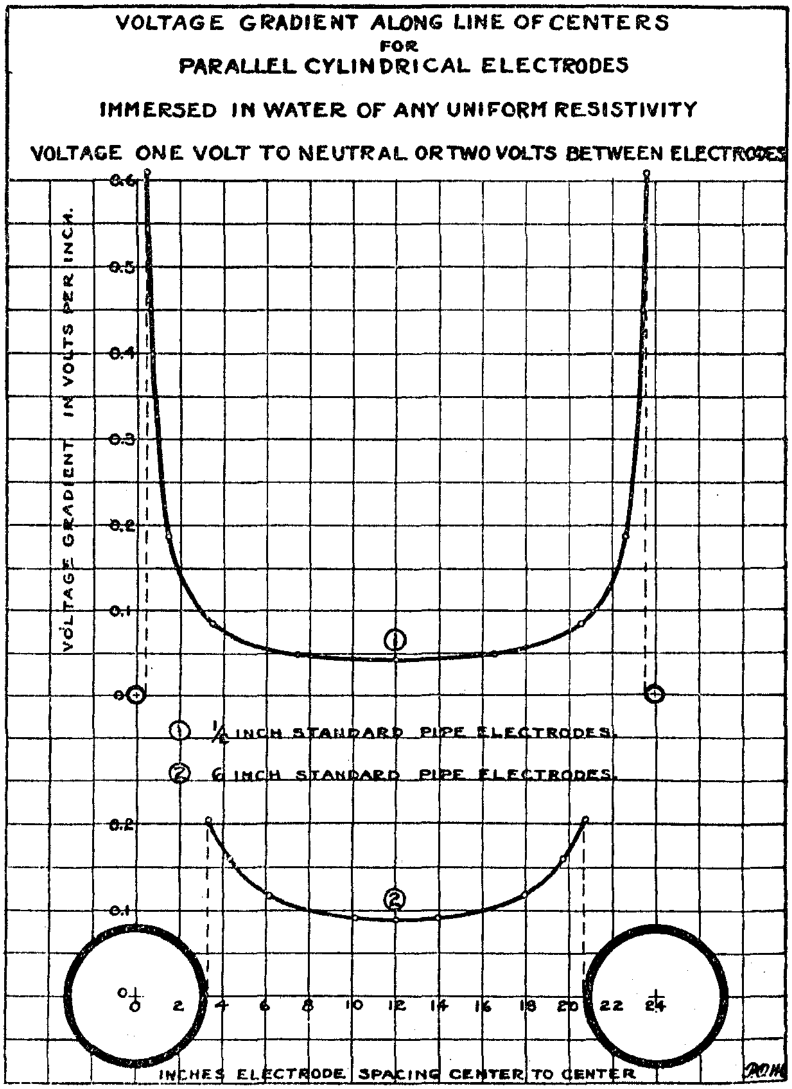

FIG. 13

The result was that during the first day there were never more than 30 fish in the protected area.

At 11.30 a. m., August 18, the second day of operation of the screen, a short circuit occurred in some very poorly insulated scrap wire it had been necessary to use in making the power extension to the transformer supplying the screen. This took the voltage off the screen until 6 p. m., during which period between 3,000 and 4,000 fish went into the protected area. These fish were coaxed out of the protected area by feeding before the screen was electrified again. This accidental interruption of the screen power supply showed two things: First, it is important to have a reliable source of supply, and, second, the screen was effectively keeping the fish out of the

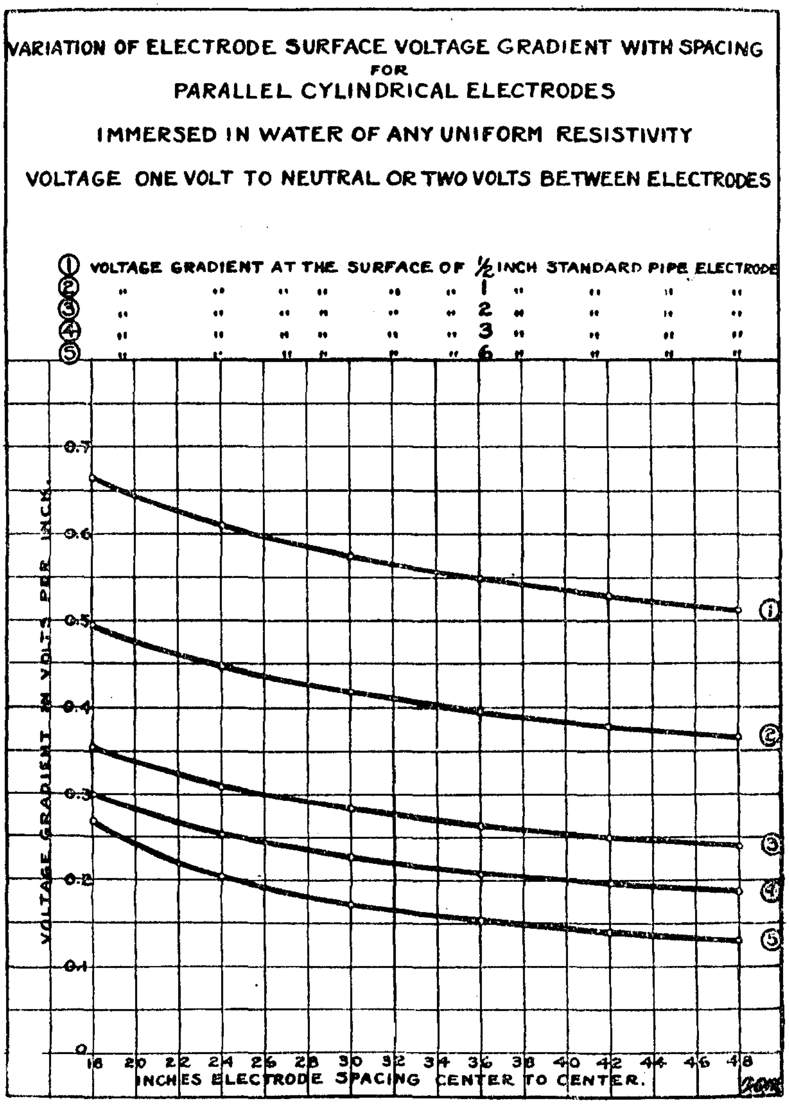

FIG. 14

protected area. Following this interruption the screen was kept electrified continuously for 10 days. During this period sunshine and cloudy and rainy weather were experienced. One very hard rain, lasting about 36 hours, occurred on August 25 and 26. This afforded an opportunity to see whether weather conditions had any influence on the effectiveness of the screen equipment, and as far as could be observed it did not have any effect. A very accurate record was kept of the fish killed during this test. The hatchery attendants were instructed not to remove any dead fish from pond No. 12 without having them properly recorded. For the entire period of 11 days (this includes August 17, the first day of the test, which was eliminated from the 10-day continuous run by a short circuit in the temporary alternating-current supply

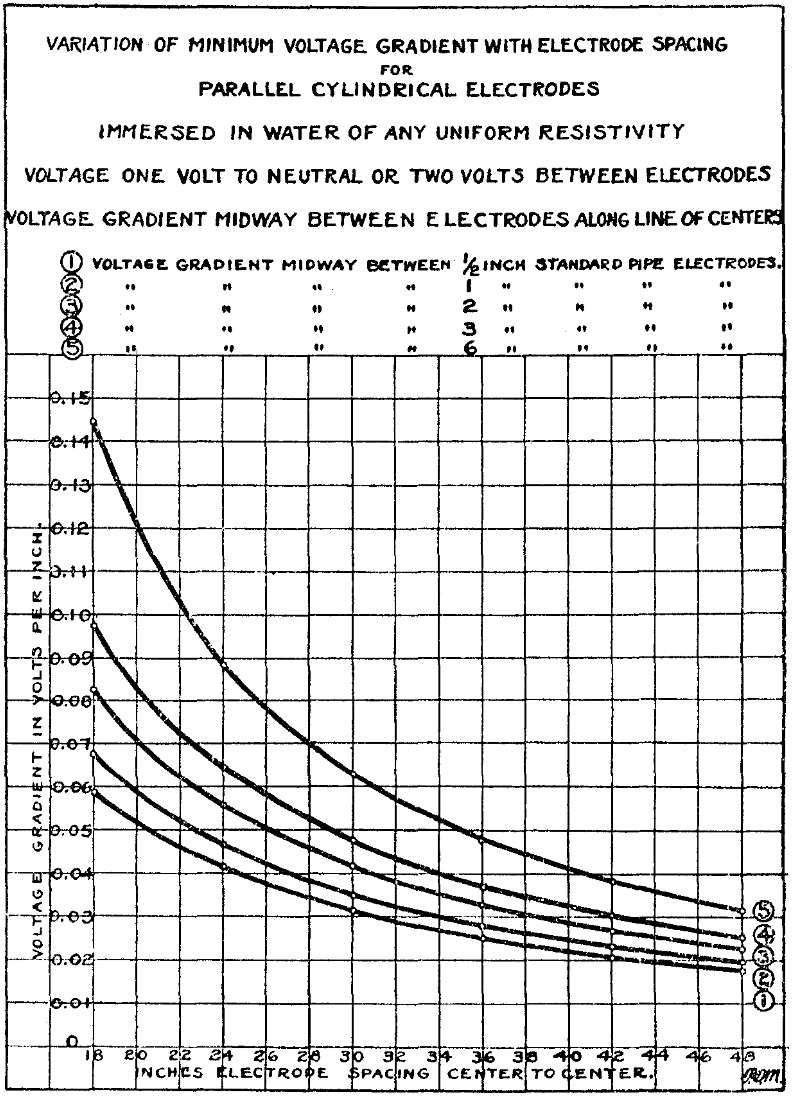

FIG. 15

line on August 18), from August 17 to August 27, inclusive, 29 fish were killed by the electric screen, or less than 0.2 per cent of the 15,000 fish in pond No. 12—a negligible number. The maximum number of fish killed in one 24-hour day was six; on two days no fish were killed; and the average number killed per day for the 11-day period was 2.64. By the use of larger-diameter electrodes (thereby obtaining a more uniform voltage gradient) even this small number of fish killed could have been reduced, if not entirely eliminated. At the time the screen equipment was disconnected (on August 28), as nearly as could be estimated 500 of the 15,000 fish were in the protected area. These had accumulated gradually during the 10-day period. The screen kept 97 per cent of the fish from the protected area, which is an excellent record. This installation was witnessed by John C. Veatch, of the Oregon Fish

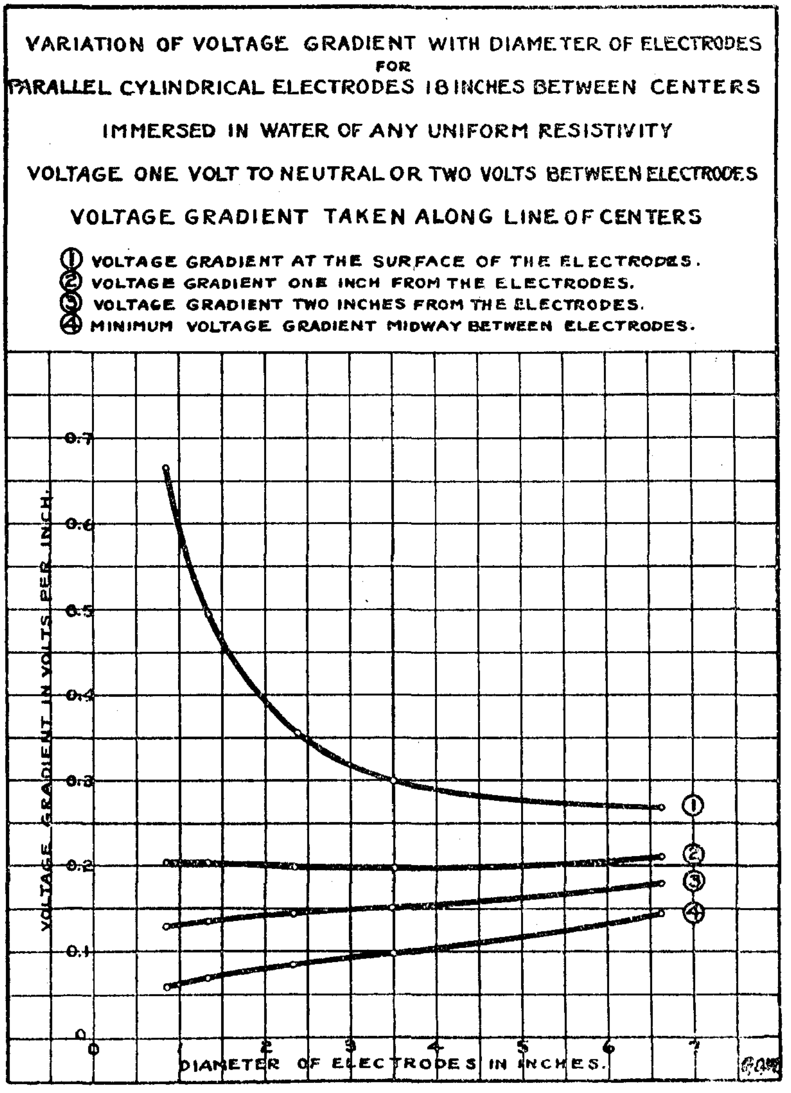

FIG. 16

Commission; Edward Balaugh, master fish warden of Oregon; E. F. Averill, master game warden of Oregon; H. B. Holmes, biologist with the United States Bureau of Fisheries; and many others. Eugene Howell, superintendent of the Bonneville hatchery, and some of his assistants made daily observations, and J. E. Yates made observations on several different days during the progress of the test.

DESIGN OF ELECTRIC FISH SCREENS

In this discussion of the design of electric fish screens no attempt will be made to discuss the details of mechanical construction, because these may be altered greatly by local conditions. The electrical design, however, is fundamental and contains

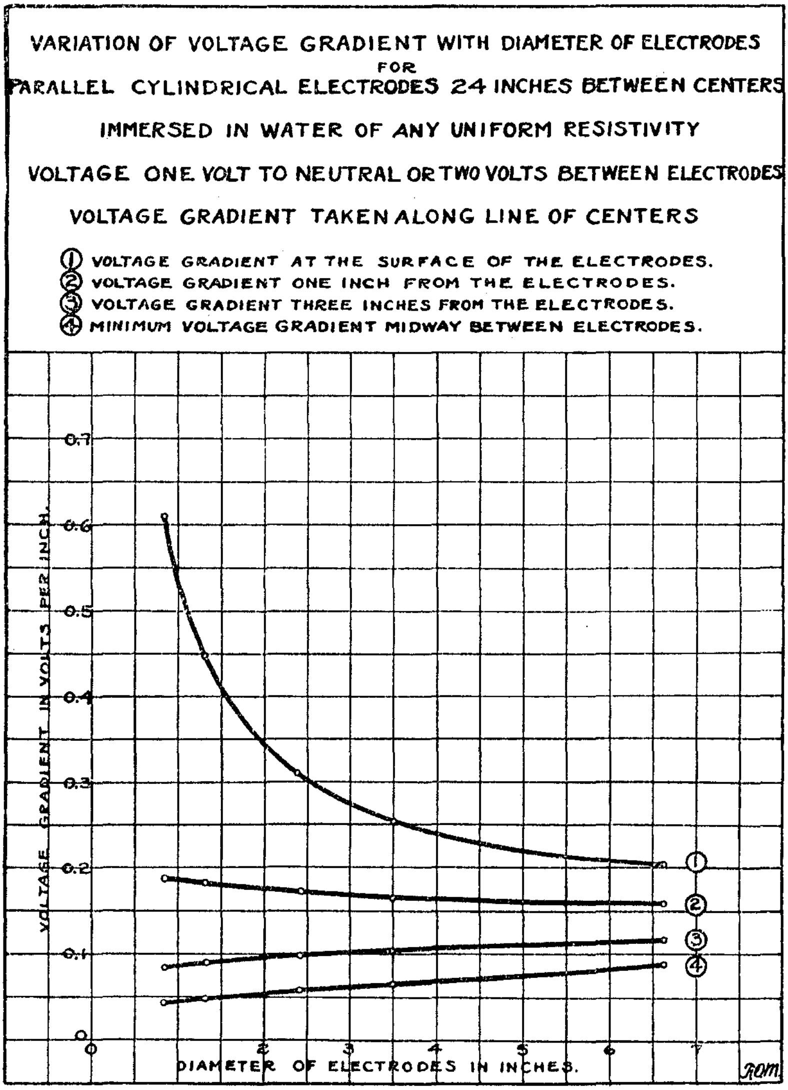

FIG. 17

conditions that must be met to obtain satisfactory operation. These conditions, stated very briefly, are as follows:

1. An insulating transformer should be used between the power supply and the screen to avoid a useless current flow from the electrodes to ground.

2. The lines of current flow in the electric field must be perpendicular to the plane of the protected opening and the equipotential surfaces parallel with this plane. (See figs. 10 and 12.)

3. The lines of electric-current flow must be parallel with the direction of the water flow. (See figs. 10 and 12.)

4. The voltage gradient in the electric field should be kept as uniform as practical by the selection of proper electrode sizes and spacing. (See figs. 13 to 21, inclusive.)

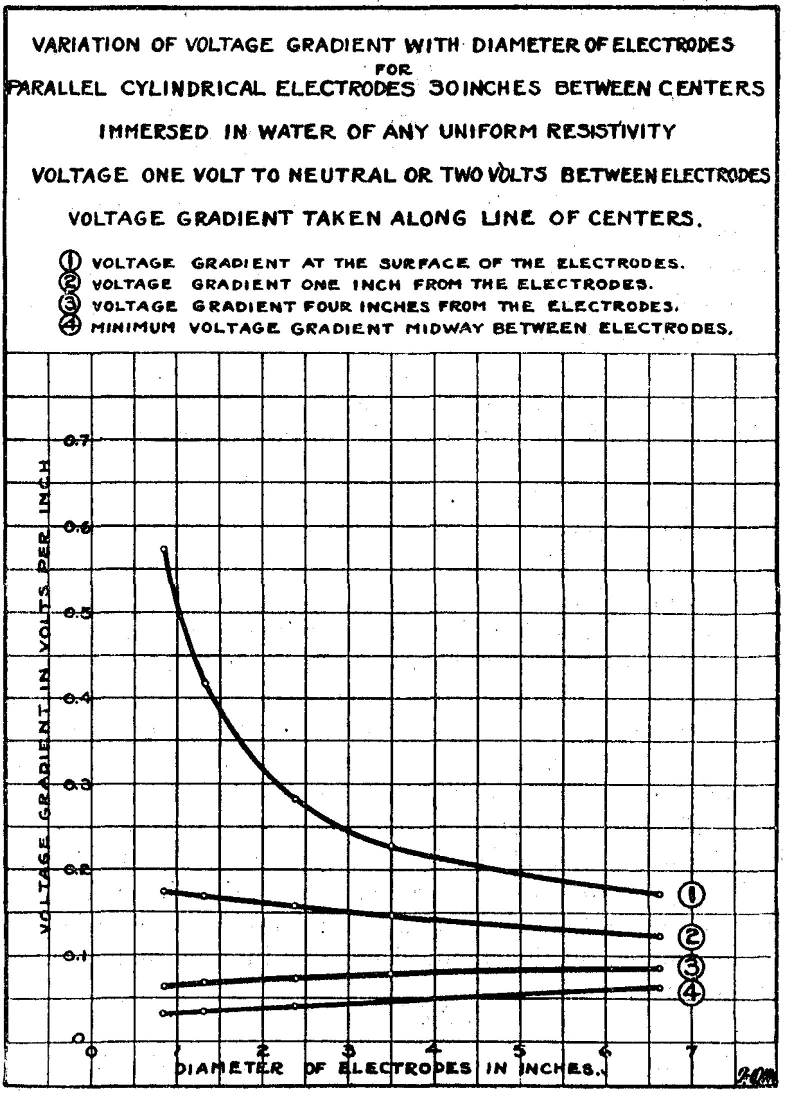

FIG. 18

5. The voltage gradient must be suitable for the size fish to be protected. If the fish to be protected vary greatly in length, it may be necessary to use a double screen. (See equation on p. 107.)

6. The spacing between electrodes in the rows is determined largely by the opening desired for débris to pass through.

7. The spacing between rows of electrodes should be approximately 1.33 times the spacing of the electrodes in the rows.

8. The electrodes should be from 2 to 12 inches above the bottom of the stream. This distance depends upon the spacing of the electrodes and upon the character of the stream bed.

The voltage gradient along the line of centers between two parallel cylindrical electrodes (which is the locus of the maximum voltage gradients) in an electrolyte of uniform resistivity, such as the water of streams, can be calculated by the use of the following equation:

$$g=\frac{E_n\sqrt{S^2-4\,r^2}}{\left\{(r+x)\;(S-2r)-x^2\right\}\log_\epsilon\left[\frac{S}{2r}+\sqrt{\left(\frac{S}{2r}\right)^2-1}\right]}$$

Where

g = the voltage gradient in volts per inch at distance x from the surface of the electrode.

E_n = the voltage to neutral (one-half electrode voltage for a single-phase circuit) root mean square values of the alternating voltages were used in this investigation.

S = the spacing, in inches, between electrode centers.

r = the radius, in inches, of the electrodes.

x = the distance, in inches, from the surface of the electrode at which the voltage gradient g is to be calculated.

ϵ = 2.7183, the base of Naperian logarithms.

To facilitate the electrical calculation of fish screens and to show how the various factors, such as electrode diameter and spacing, influence the voltage gradient, Figures 12 to 21, inclusive, were calculated and plotted. Figure 12 is the plot of the lines of current flow and equipotential surfaces for two standard 6-inch pipe electrodes, spaced 24 inches, center to center. In Figure 13, 1 and 2 are the voltage-gradient curves along the line of centers for ½-inch and 6-inch standard-pipe electrodes. These curves clearly show the importance of using large-diameter electrodes for improving the voltage gradient. Figures 14 and 15 show the variation of the maximum and minimum voltage gradients along the line of centers for various electrode spacings. Figures 16 to 21, inclusive, show the variation of voltage gradient along the line of centers, with electrode diameter for 18, 24, 30, 36, 42, and 48 inch electrode spacing, center to center. The diameters plotted in these curves are actual outside diameters and not nominal pipe sizes; however, the various sizes of pipe electrodes are designated by the standard nominal internal diameter by which they are known to the trade.

CONCLUSIONS

The following conclusions were reached from this investigation:

1. A very simple relation exists between the minimum voltage gradient required to paralyze fish and their length, which can be expressed by the equation

$$g=\frac{3.70\,W}{L}$$

where g = voltage gradient in volts per inch, W = water-resistivity correction factor, and L = length of fish in inches.

2. When voltage gradients above the paralysis values are applied to fish, the mortality increases with increased time of application.

3. Fish subjected to electric shocks in various degrees, if not killed outright, quickly recover and do not suffer any serious after effects.

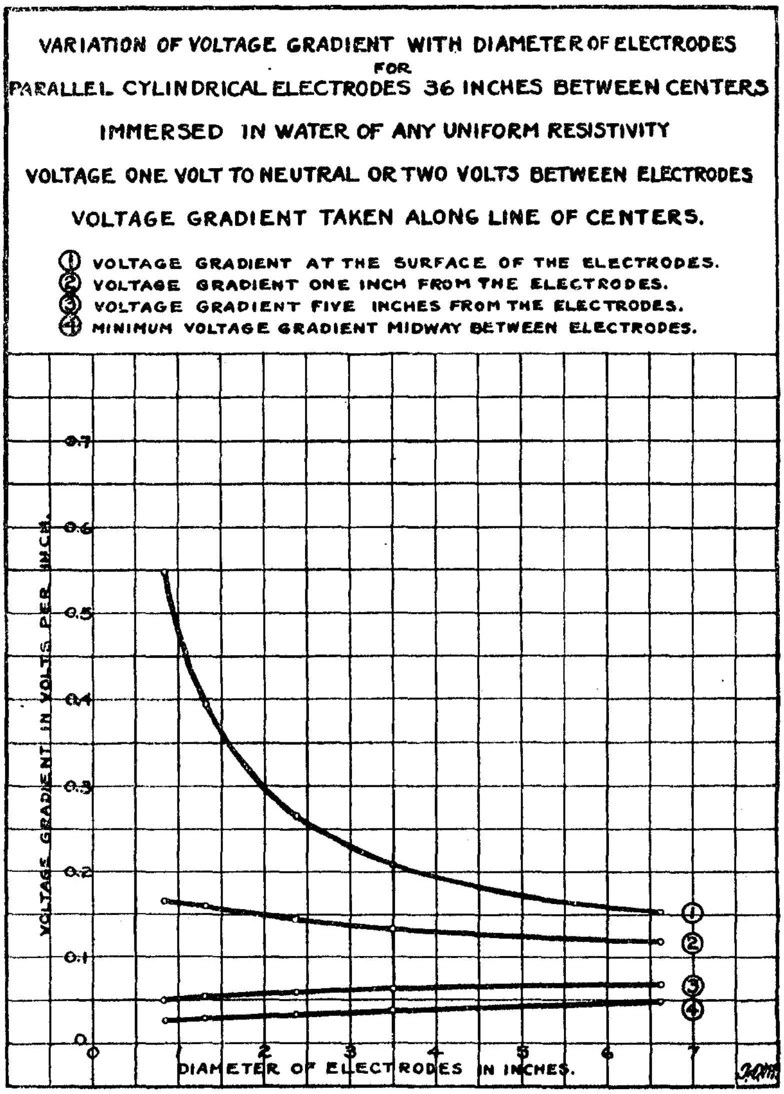

FIG. 10

4. The resistivity of the water in which fish are immersed has an important influence upon the voltage gradient required to produce paralysis, as shown by the values of the water-resistivity correction factor, "W" in Table 4.

5. Very large variations are found in the resistivity of the water from various streams. The largest fresh-water variation found was one river water that had a

resistivity 12.3 times that of the lowest stream-water resistivity found. The highest resistivity river water had a resistivity 880 times that of sea water. In spite of this wide variation in resistivity, the temperature-resistivity curves for waters from all of the 16 sources of water studied can be represented over the range of temper-

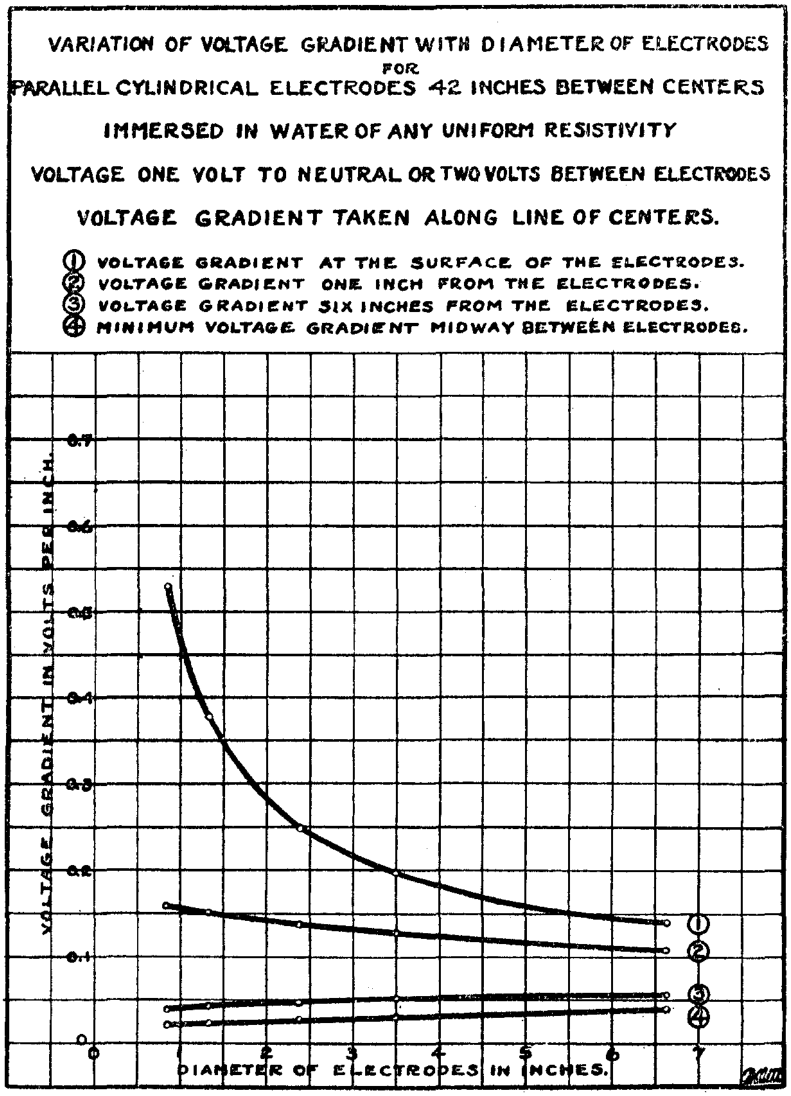

FIG. 20

ature from 40 to 100° F. by the equation

$$\rho = A\epsilon^{-0.014\,\Theta}$$

where ρ = the resistivity in ohms per inch cube, A = a constant different for each kind of water (see Table 5), ϵ = 2.7183 base of Naperian logarithms, and Θ = the water temperature in degrees Fahrenheit.

6. When swimming into an electrified area fish do have a sense of the direction of danger and try to avoid it.

7. To be effective, an electric screen must have the lines of current flow perpendicular to the plane of the protected opening and the equipotential surfaces parallel

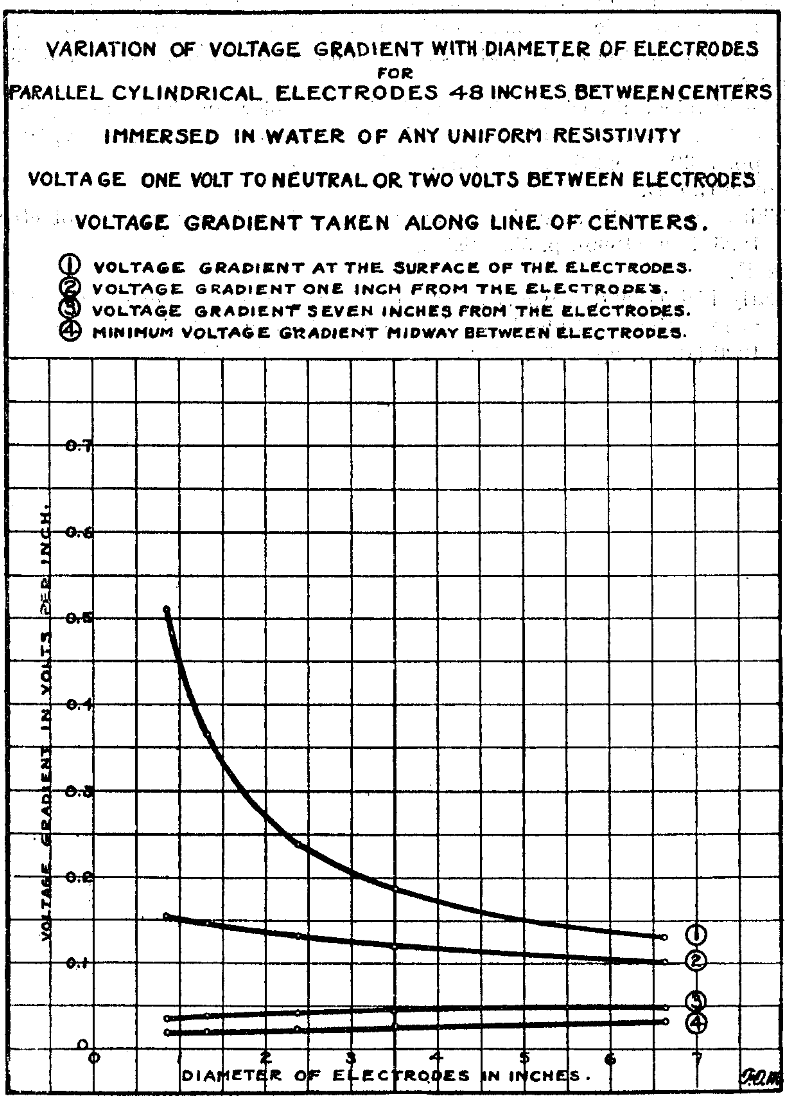

FIG. 21

with this plane. The lines of electric-current flow must also be parallel with the direction of stream flow.

8. The experimental electric fish screens have been very successful. Actual stream installations should now be made, carefully observed, and developed.

BIBLIOGRAPHY

BURKEY, HENRY T.

1924. United States patent No. 1515547, Electric Fish Stop. November 11, 1927. Washington.

KOHLRAUSCH, FRIEDRICH WILHELM GEORG.

1883. Introduction to physical measurements, with appendices on absolute electrical measurements, etc. Second English edition, from fourth German edition, by T. H. Waller and H. R. Proctor, pp. 215–218. J. and A. Churchill, London, 1883.

KUNTZ, ALBERT.

1917. The histological basis of adaptive shades and colors in the flounder, *Paralichthys albiguttus*. Bulletin, United States Bureau of Fisheries, Vol. XXXV, 1915–1916 (1918), pp. 1–30, 8 text figs., Pls. I–II. Washington.

McGUIRE, HOLLISTER D.

1896. Third and fourth annual reports of the State fish and game protector [of Oregon], 1895–1896 (1896), p. 53. Salem.

RICH, WILLIS H.

1920. Early history and seaward migration of chinook salmon in the Columbia and Sacramento Rivers. Bulletin, United States Bureau of Fisheries. Vol. XXXVII, 1919–1920 (1922), pp. 1–74, Pls. I–IV, 9 graphs. Washington.