DIRECTING THE MOVEMENT OF FISH WITH ELECTRICITY

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Explanatory Note

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United States Department of the Interior, Douglas McKay, Secretary
Fish and Wildlife Service, Albert M. Day, Director

DIRECTING THE MOVEMENT OF FISH WITH ELECTRICITY

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Special Scientific Report: Fisheries No. 93

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ILLUSTRATIONS

DIRECTING THE MOVEMENT OF FISH WITH ELECTRICITY[1]

Introduction

The Fish and Wildlife Service's Great Lakes Fishery Investigations (under the direction of Dr. James W. Moffett) has recently developed alternating current electrical devices which appear most promising as a means of controlling the parasitic sea lamprey in the Great Lakes.[2] Observations on these electrical devices demonstrated some need for developing a means of accelerating the capture and transfer upstream of fish migrating during the period of sea lamprey movement. This study represents one phase of the work undertaken to solve that problem. The experiment was based on the assumption that local food and game fish would move involuntarily toward the positive electrode when exposed to an appropriate type of direct current introduced into the water.[3] If fish movement could be thus controlled with a simple accessory mechanism (to the AC sea lamprey control devices), it would resolve the problem in some stream locations of providing for uninterrupted migrations of fishes while blocking or otherwise destroying the sea lamprey runs.

The examination of literature available at the time the study was undertaken failed to yield clear-cut information on the behavior of fish subjected to direct electrical currents or on direct current electrical devices that might be employed to lead fish. Therefore, the first part of this investigation was directed toward determining the type of electric current that would be most effective in controlling the movements of fish. The second phase constituted the investigation of those factors which would affect the efficiency of an electrical leading device as it might be used as an aid in trapping fish to minimize the blocking effect of an alternating current, electrical sea lamprey barrier.

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[1] This study was conducted under the direction and supervision of Dr. Vernon C. Applegate, In Charge of Sea Lamprey Investigations, Hammond Bay Fishery Laboratory, Rogers City, Michigan.

[2] Applegate, Vernon C., Bernard R. Smith, and Willis L. Nielsen. Use of Electricity in the Control of Sea Lampreys: Electrc-Mechanical Weirs and Traps and Electrical Barriers. (Scheduled for publication as a Special Scientific Report, U. S. Department of the Interior, Fish and Wildlife Service).

[3] Personal communications with staff members of the California Academy of Sciences, Golden Gate Park, San Francisco, California.

Equipment

A reinforced concrete tank, equipped with an electrically insulating liner, was used for the laboratory experiments. The insulating liner was installed to prevent distortion of the electrical field pattern by the highly conductive materials of the tank (reinforcing steel). The inside dimensions were 210 inches long, 36 inches wide, and 36 inches deep. A continuous flow of water was pumped from Lake Huron into the tank during the tests. The depth was held at 12 inches by means of a non-conducting overflow tube.

The electrodes used in the laboratory tests were two 36-inch-square pieces of 1/2-inch-mesh galvanized hardware cloth. These electrodes were suspended vertically 2 inches from either end of the tank and perpendicular to the long axis of the tank. The immersed area of each electrode was then 36 inches wide and 12 inches high. A barrier of small-mesh cotton netting mounted on a wooden frame was placed across either end of the tank 6 inches from the electrode and parallel to it. These barriers protected the test animals from direct contact with the electrodes.

A direct current power supply in combination with a motor-driven switch (or commutator) provided the electrical impulses used in the fish leading experiments. A variable transformer, connected to a 220 volt AC domestic line supplied any desired voltage up to 260 volts AC to the primary of a power transformer. The power transformer, having a 2 : 1 step-up ratio and a center-tapped secondary winding, supplied power to a pair of selenium rectifiers which were controlled by a switch to form either a half- or full-wave rectifier circuit.

The full-wave circuit delivered up to 260 volts of DC at 12.5 amperes, with a ripple frequency of 120 cycles per second, while the half-wave circuit supplied up to 500 volts DC at the same current and half the ripple frequency. Inasmuch as the output of the rectifier was filtered when square wave pulses were desired after commutation, the difference in ripple frequency is of little importance. In addition to square wave pulses, the unit could be used to supply continuous filtered DC or unfiltered DC at ripple frequencies of 60 cycles (half-wave rectification) or 120 cycles (full-wave rectification) in continuous or commutated form. The power supply, originally intended for field experiments in which large power requirements were anticipated, might easily have been replaced by a smaller unit providing the same voltage range at the low current levels encountered in the insulated test tank. The 12 inches of water in the tank presented a load of approximately 1,270 ohms to the power source.

The commutator used in the first phase of the experiments was constructed to allow flexibility in the choice of duty cycle and repetition rate.[4] This unit, which provided pulsed or interrupted DC, consisted of a single switch driven by a controllable-speed motor through a reduction gear and cam shaft. Four interchangeable cams were used to provide duty cycles of 0.025, 0.10, 0.25, and 0.66. A variable transformer, supplying power to the motor, was used to adjust the cam shaft speed from 1 through 5 revolutions per second with each revolution of the cam shaft producing one pulse. Thus it was possible to check the reactions of the test animals at 20 combinations of repetition rate and duty cycle for each voltage level investigated.

The results of the initial tests to determine the combination of variables most effective in leading fish indicated the choice of square-wave pulses at a duty cycle of 0.66 and a repetition rate of 3 per second. In the second series of tests, conducted to determine the voltage gradients required to lead adult rainbow trout (Salmo gairdneri) of different sizes, the repetition rate and duty cycle were held at the above values, while the pulse voltage level was varied. In order to facilitate the conduct of these and other tests, the commutator unit was modified to produce pulses at a fixed duty cycle of 0.66, with provision for easy selection of any repetition rate by means of a plug and jack board, without the necessity of changing cams or motor speed. This selection of repetition rate was accomplished by the use of cam and switch assemblies, driven by a controllable-speed motor through a reduction gear. These 5 cams produced 1 through 5 pulses per revolution of the shaft. A revolution counter coupled to the cam shaft permitted the motor speed to be adjusted to a value that resulted in one revolution of the shaft per second.

Electrode voltage and current could be measured and adjusted in the steady-state condition before test specimens were placed in the tank. Adjustment of the electrode voltage, (i.e., the peak voltage under pulsed operation) was accomplished by means of the 220 volt AC variable transformer. A switch in the output of the DC power supply and commutator unit permitted the polarity to be reversed at will, thus reducing the likelihood of conditioned response in the test animals. A neon bulb connected directly across the electrodes provided a convenient visual check of the operation of the power supply and the commutator and of the polarity. Two red warning lights, energized by the contactor which supplied power to the 220 VAC variable transformer, served as a constant reminder of the existence of high voltages in the experimental area. A diagram of the electrical equipment is shown in Figure 1.

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[4] The term duty cycle may be defined as the ratio of "on" time to total time between leading edges of successive pulses. This ratio is determined by the cam configuration. Repetition rate (the number of pulses per second) is controlled by the speed of cam rotation.

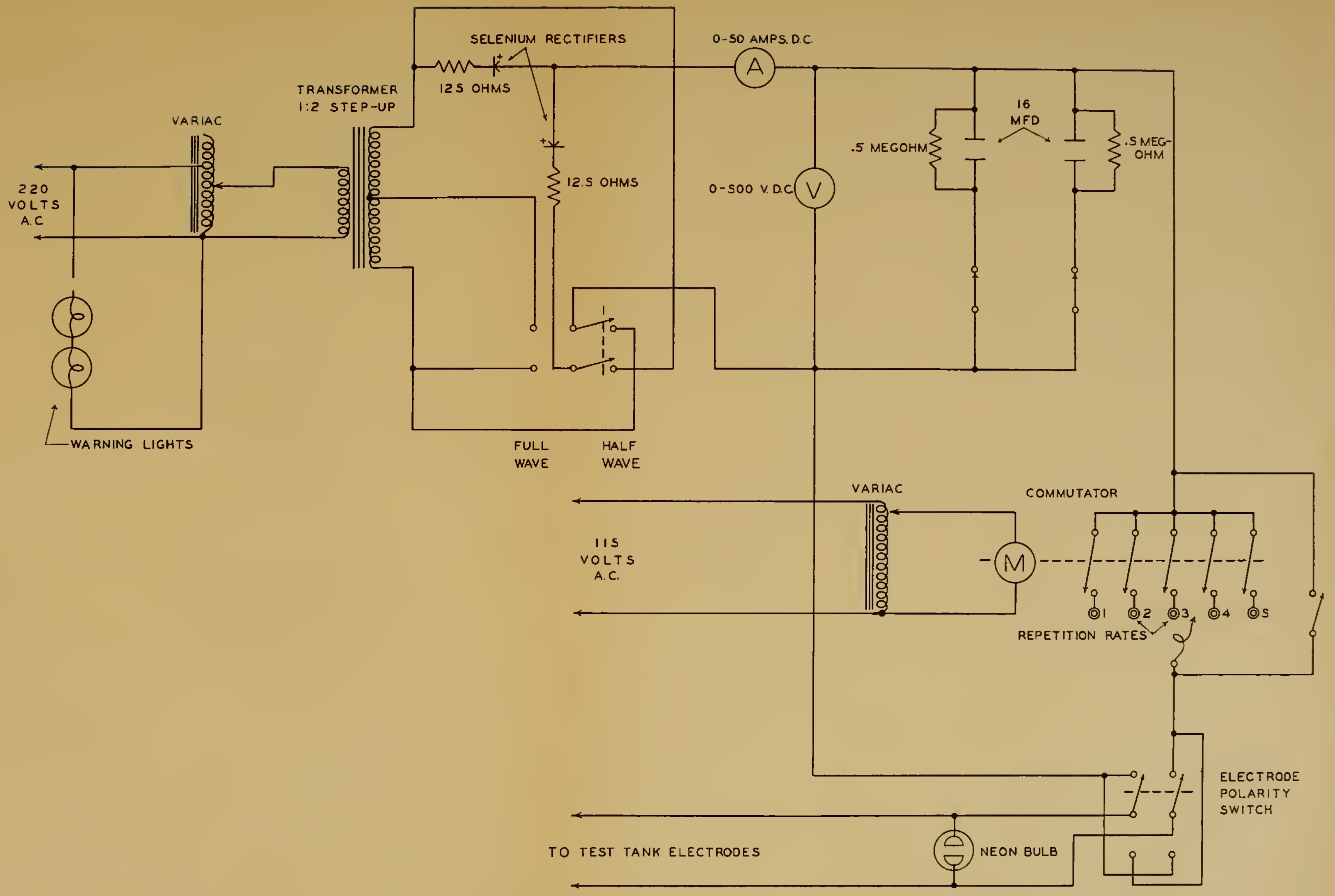

Fig. 1--Diagram of electrical equipment used in fish leading experiments

The relative water voltage gradients plotted in Figure 2 were determined with AC voltages applied to the electrodes. These gradients were considered to approximate closely those which existed when pulsed direct current was used. The measuring equipment consisted of a General Radio Type 727-A high-impedance vacuum tube voltmeter and a specially designed voltage gradient probe.[5] All measurements were taken at points halfway between the surface and the bottom along a line through the centers of the electrodes. The ideally uniform voltage gradients produced in the test tank were not duplicated in experiments conducted in the field. The difference can be attributed to the confinement of the test-tank electrode current to an insulated body of water whose cross-sectional area was equal to the immersed electrode area.

Field tests were conducted at Carp Creek and the Little Ocqueoc River, Presque Isle County, Michigan. A mechanical weir trap of 1/2-inch-mesh hardware cloth (modified Milligan Creek type, Applegate and Smith, 1950) (selected because of its ready availability) was used as the positive electrode for the field tests. This trap had an opening approximately 18 inches square and was situated at the apex of a "V" formed by 2 frame-mounted pieces of cotton-cloth netting. Each piece of netting was 3 feet long and together they functioned as a funnel. The cathode was a section of 1/2-inch-mesh hardware cloth 6 feet wide and 2 feet high. The electrodes of the Carp Creek array were spaced 20 feet apart and placed on a line almost directly across the stream. The Little Ocqueoc River array was the same except that the distance between electrodes was only 10 feet (Fig. 3).

Field tests at the Carp Creek and Little Ocqueoc River sites were conducted with the DC power supply and commutator unit previously described in this section. This unit, mounted in a trailer, was powered by a 5 KW 110/220 VAC, diesel-driven generator (Fig. 4).

Methods

The initial tests were conducted in an attempt to find the best combinations of variables to produce the desired leading effects. The cam producing a duty cycle of 0.025 was installed and each repetition rate (1 through 5 cycles per second) was tested at a specific voltage level. The voltage input was then increased and tests were again made at each repetition rate. Usually a series of tests started with a voltage input that had little effect on the test fish and the voltage was increased in increments of 10 volts until the test animals were electronarcotized.

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[5] See footnote 2.

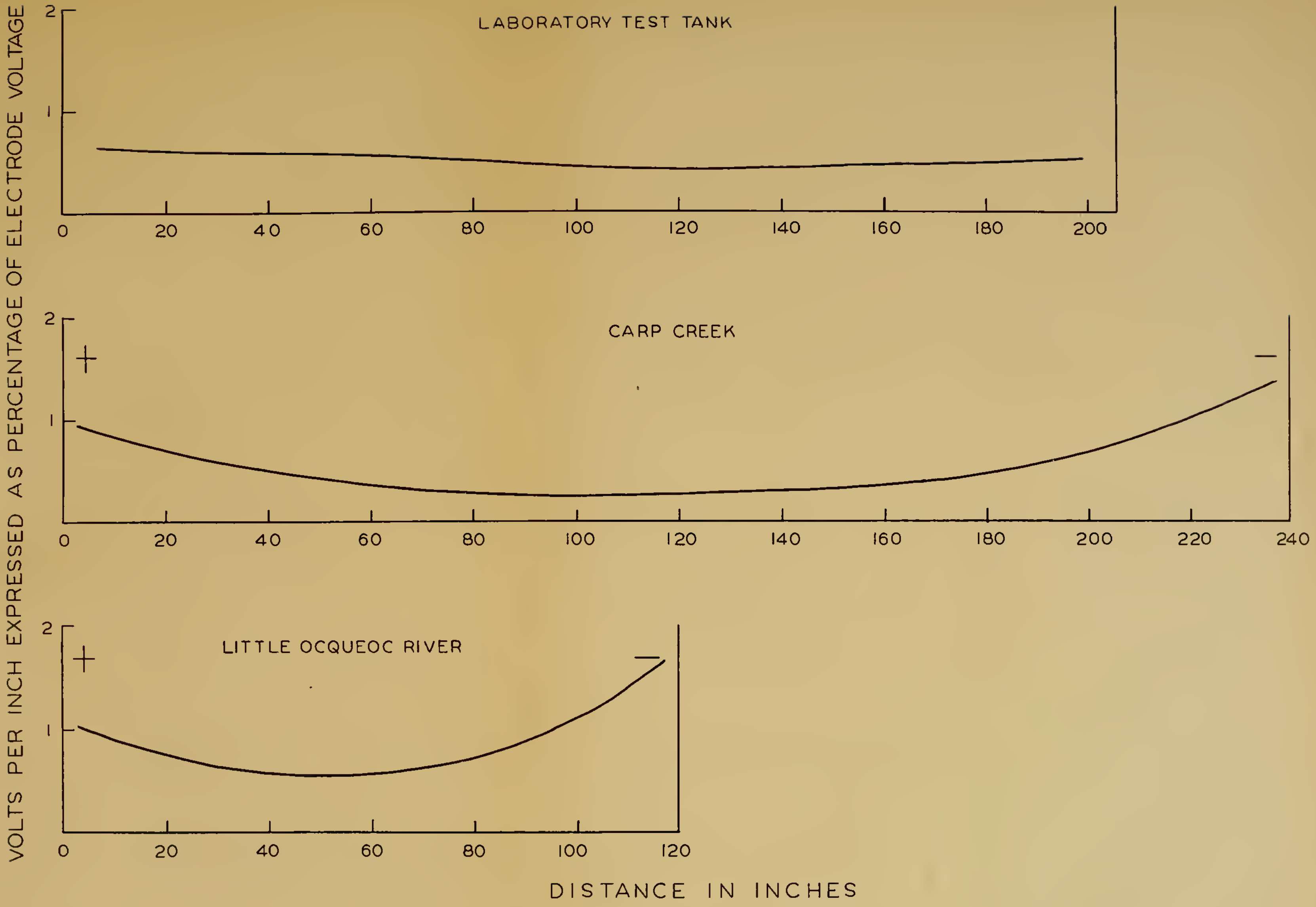

Fig. 2--Voltage gradients in volts per inch (expressed as percentage of electrode voltage) obtained between electrodes (distance in inches) in the laboratory test tank, Carp Creek, and the Little Ocqueoc River.

Figure 3.--The electrode array of the DC leading device as installed in the Little Ocqueoc River, Presque Isle County, Michigan.

The procedure was then repeated with the cams which produced duty cycles of 0.10, 0.25, and 0.66 respectively. White suckers (Catostomus c. commersoni) and brook trout (Salvelinus f. fontinalis) used in these initial experiments were held in various facilities available at the Hammond Bay Laboratory. Reasonable precautions were exercised in maintaining and handling the test animals. At all times water temperature in the test tank was held within 3° F. or less of that of the holding tanks and pens.

The advisability of allowing the test animals to become acclimated to conditions in the test tank was considered. However, no visible difference could be observed in the results obtained with brook trout subjected to a test immediately after being placed in the tank and those tested after being in the tank from 2 to 48 hours. This result was perhaps to be expected inasmuch as the desired reaction was a stimulated movement not consciously controllable by the fish.

Originally it was planned to employ 6 fish for each test; however, it became obvious that unless the test animals were used several times an excessively large number of fish would be required. A small

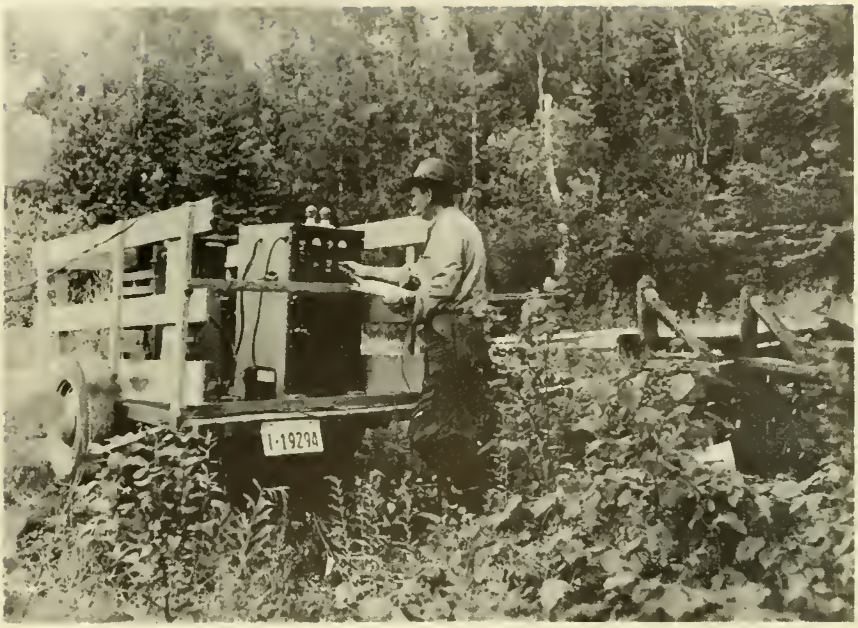

Figure 4.--The DC power supply and commutator unit of the leading device as used for field tests.

portion of the suckers were used a second time but only after a lapse of at least 2 days. In tests conducted below the critical voltage level, brook trout ordinarily displayed so much activity that observations of results with 6 specimens became difficult. As a result, the number was reduced to a single fish per test with checks made on groups of 3 or 5 when results indicated the need.

In general, the fish were placed in the tank, allowed to position themselves at will, and then the power was applied. Usually the electrode most distant from the fish was made positive. Polarity was reversed at random intervals 2 to 4 times during each test.

The second phase of the laboratory experiments was concerned with the relationship between voltage gradient and size of fish. The most effective combination of duty cycle and repetition rate, established from the first experimental phase, was applied throughout the series of tests. Two hundred seventy-nine rainbow trout ranging from 9.2 to 24.5 inches were used as test specimens in these experiments. The test procedure as previously described was followed. Each rainbow trout was subjected to only one test to eliminate the possibility of any residual effect of a previous electrical shock on its reactions.

The methods followed in experiments conducted in the field were generally comparable to those used in the laboratory tests, although procedures were varied slightly according to conditions encountered at the field sites. Further details are given in the discussion of the results.

Reactions of different species to pulsated direct current

The results of 798 tests on more than 1,000 fish proved that some species when subjected to an applied voltage gradient of pulsated direct current under given conditions can be made to move toward, or be assembled at, the anode or positive electrode. It was determined in the tests that fish of a particular size led best at a definite voltage level. If the voltage gradient lies within the effective range for the size of the fish, the movement to the anode will be immediate and determined. The results described in this study are based on the reactions of white suckers, brook trout, and rainbow trout.

Laboratory tests on white suckers.--Nearly 250 tests were conducted in the laboratory with white suckers which ranged in length from 9 to 16 inches. They were subjected to a series of tests encompassing the entire range of variables which the equipment was capable of producing. The water temperature throughout the laboratory experimentation varied from 36° to 39° F.

The tests failed to elicit from the suckers a definite movement toward the anode or even any indication of orientation to the flow of electrical current. Some of the tests appeared to indicate a trend of movement to the anode end of the tank; however, rechecks and additional tests invariably failed to yield confirming results. The voltage gradient required to produce electronarcosis varied inversely as the duty cycle.

Field tests on white suckers.--The results of the field tests on leading white suckers were exactly opposite those obtained in the laboratory, in that very positive involuntary and persistent movement toward the anode was observed. The device was installed in Carp Creek which was approximately 25 feet wide and averaged 18 inches deep at the experimental site. During the testing period, water velocity was almost negligible and water temperature ranged from 75° to 78° F. The electrode array was as described in the section on equipment.

Only 11 suckers were available for experimentation; these fish had been captured in a mechanical weir and trap located just below the leading device. The fish were subjected to essentially square waves of pulsated direct current at a duty cycle of 0.66 and a repetition rate of 3 pulses per second. Tests were made at two levels of electrode voltage, 150 and 170 volts peak. The electrode current at 150 volts was 3.5 amperes resulting in a peak load of 525 watts. The resultant voltage gradient which was produced in the water between the electrodes is illustrated in Figure 2. A fairly intense electrical field existed near each electrode with the lowest voltage midway between them. The gradient could have been made more uniform between electrode centers by increasing the immersed area of both electrodes. The presence of a higher voltage gradient at the cathode in both of the field installations (Carp Creek and Little Ocqueoc River) is probably due to the greater effective immersed area of that electrode.

The 11 suckers were tested individually. Eight of them definitely responded to polarity by displaying an immediate movement toward the anode. Of the three that failed to respond, one escaped upstream from the center of the electrical field, and 2 were electronarcotized immediately upon the application of power. In addition, 2 "free" suckers accidently entered the area and both went directly to the anode.

Although the number of tests at Carp Creek was so small that conclusions are limited, the behavior of the few fish indicated beyond any reasonable doubt that a suitable galvanotaxic response could be induced among suckers. The low water temperatures may have been the reason for the failure of suckers to respond in the test tank, especially in view of the fact that electrical conditions in the laboratory were experimentally more ideal.

Laboratory tests on brook trout.--The second series of tests in the laboratory was made with brook trout, ranging in length from 7.3 to 11.5 inches. The water temperature during the tests remained between 36° and 38° F. Brook trout swam immediately and persistently to the positive pole when subjected to the proper voltage gradient of pulsated direct current.

Voltage levels causing electronarcosis in brook trout varied inversely as the duty cycle. A similar relationship existed in the attainment of a good response (Fig. 5); therefore, a duty cycle of 0.66 was concluded to be the most desirable since it permitted the use of the lowest voltage levels.

Within limits, the repetition rate (pulses per second) was not extremely critical. Excellent responses were obtained from the brook trout at 2 to 4 pulses per second. However, a lower repetition rate often allowed the fish to make a turn during the "off" period, and a higher repetition rate resulted in galvanotaxic reactions comparable to those encountered in tests with continuous direct current. In general, an application of continuous DC will produce a response to polarity but the ability of the fish to move appears restricted.

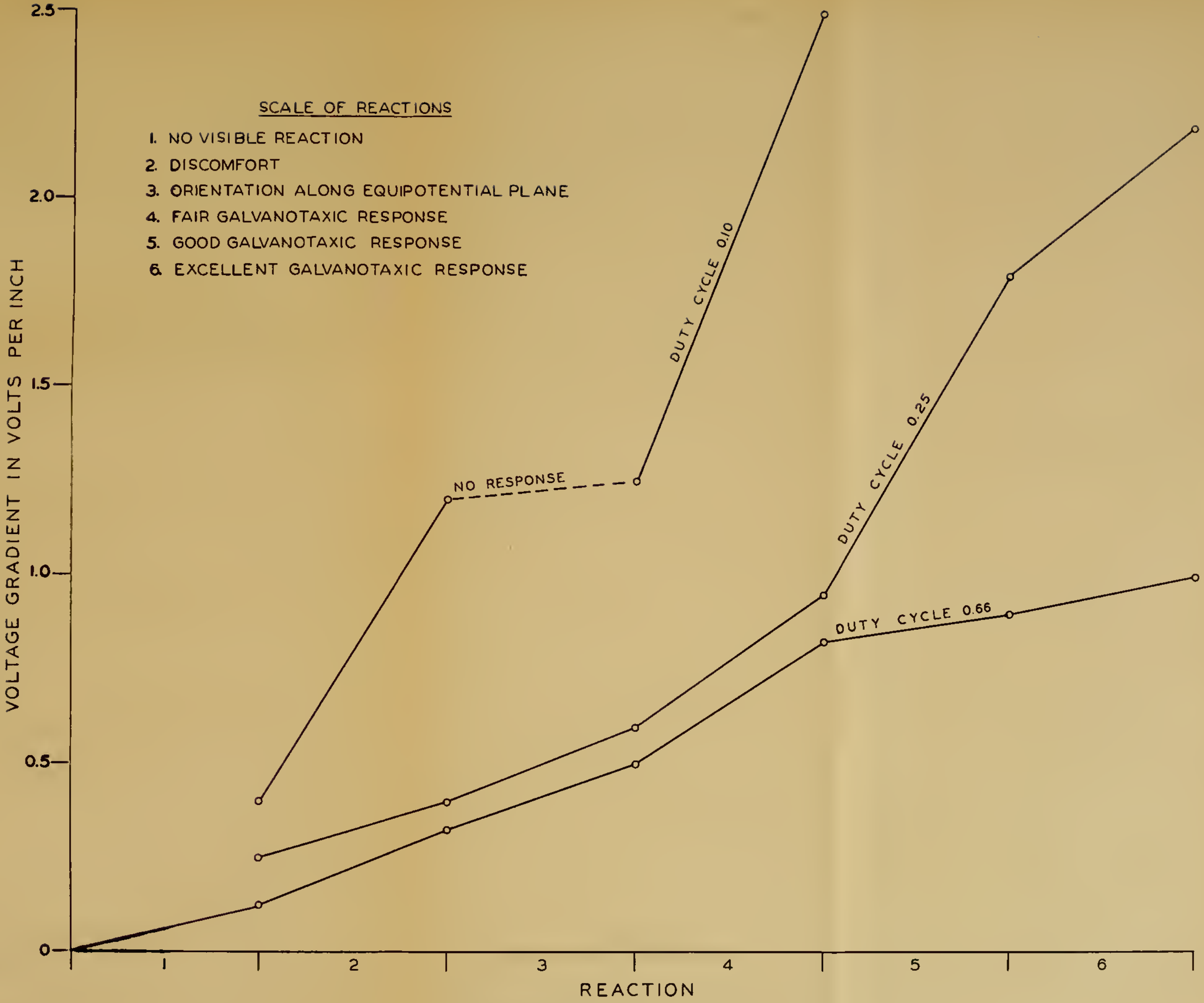

Fig. 5—The influence of voltage gradient and duty cycle at a repetition rate of 2 pulses per second on the galvanotaxic reactions of brook trout. Lines between points indicate range of voltage gradient over which the class of reaction was observed.

The variations in the galvanotaxic response of the brook trout with respect to voltage gradient and duty cycle are also shown in Figure 5. At low voltage gradients the response of the brook trout indicated only discomfort, whereas at a higher voltage gradient, but one still below those which stimulated movement toward the anode, the reaction of the majority of the brook trout was persistent alignment along equipotential planes or at right angles to the flow of current. In contrast, the white suckers appeared to assume this position only by chance and could be easily driven from it. At still higher voltages, brook trout showed good response after a period of violent circling. With additional increases, voltage levels were reached which produced immediate and determined movement to the anode.

Laboratory tests on rainbow trout.--Two hundred seventy-nine adult rainbow trout, ranging in length from 9.2 to 24.5 inches, were used in a series of tests to determine the relationship between voltage gradient producing the desired response and the size of the fish. Duty cycle and repetition rate were held constant at 0.66 and 3 pulses per second, respectively. The water resistivity throughout the tests was approximately 3,000 ohms per inch cube. For the purpose of testing, the fish were divided into 16 one-inch length classes.

It would have been desirable to test each individual fish throughout a range of voltage gradients. This procedure was inadvisable because fish that had been subjected to a series of exposures were electronarcotized in subsequent exposures at a lower voltage level than that which originally would produce the same condition. Therefore, each rainbow trout was subjected to only one voltage gradient.

The response of each fish could be classified into one of 7 reasonably distinct types of reaction as listed below:

1. None..............No response to polarity.
2. Poor..............Fish meandered and circled considerably before displaying response to polarity.
3. Fair..............Fish, with little circling, went to the anode.
4. Excellent.........Response immediate and determined.
5. Good..............Good response, but movement weak--voltage a little too high.
6. Over-control......Voltage excessive, movements exaggerated and devious, electronarcosis imminent.
7. Immediate electronarcosis.

For purposes of condensation, the classification of response types "excellent" and "good" are combined in Table 1, since both responses were satisfactory. In addition, incapacitation as used in the Table includes both "over-control" and "immediate electronarcosis". An arbitrary numerical value was assigned to each type of response listed in the table and the average rank of response was computed for each size class. An inspection of the average rank of response for each group indicates the trend of the relationships among size, voltage gradient, and response. The information is summarized in Table 2 which presents the average rank of response for each 1-inch size class at the various voltage gradients. The true relationship is no doubt obscured because of the paucity of representatives in the majority of the size classes.

For each size class tested, the desired galvanotaxic response could be elicited over a definite range in voltage gradient. Similarly, a given voltage gradient stimulated the desired movement in several 1-inch classes. The exact range of effective voltage gradients was not clearly determined for each size class because of a lack of specimens. It appears that a large portion of the smaller fish would respond favorably over a rather wide range in voltage gradient. For the 13- and 14-inch length classes the effective range extended over approximately 0.22 volt. The data tend to indicate also that the effective range decreases with an increase in length of the test animals.

The limits of size in which a given voltage gradient is effective are not readily discernible. For instance, an applied voltage gradient of 0.48 volt per inch may affect the majority of rainbow trout 18-22 inches long, with its maximum effectiveness probably applicable to 20-inch fish. That same voltage gradient would be too high for the majority of trout above 22 inches in length and too low for trout falling below 18 inches. However, as indicated in Table 1, a good response was obtained from one trout only 15 inches long which was subjected to 0.48 volt per inch. Another 15-inch trout was electronarcotized at a still lower gradient, 0.37 volt per inch. Similar examples of variability or individuality displayed by the test animals were noted throughout the experiment. They contributed considerably to the variability of the data.

Field tests on rainbow trout.--Only 34 adult rainbow trout were available for the field tests which were conducted in the Little Ocqueoc River. The stream was approximately 15 feet wide, 9 to 15 inches deep, and had a maximum water velocity of slightly under 2 feet per second at the experimental site. Water temperature remained at 62° to 63° F. throughout the testing period. The stream bottom consisted of a mixture of fine and coarse gravel with some scattered small rubble. The trap (anode) was installed in 14 inches of water, and the cathode was placed along the opposite bank in 9 inches of water. The small size of the stream limited the distance between the centers of the electrodes to 10 feet. Below the device, the stream was blocked by a seine to confine the fish to the experimental area.

Table 1. Numbers of rainbow trout exhibiting various types of galvanotaxic response in relation to voltage gradient

(Data are given separately for 1-inch length groups)

Length of fish (inches)[1]	Type and rank of response	Voltage gradient (volts per inch)														
		0.26	0.32	0.37	0.42	0.48	0.53	0.58	0.64	0.68	0.74	0.80	0.84	0.90	0.95	1.0
9	0 - No response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	1 - Poor response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	2 - Fair response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	3 - Good response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	1
	4 - Incapacitation	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	Average rank	...	...	...	...	...	...	...	...	...	...	...	...	...	...	3.0
10	0 - No response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	1 - Poor response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	2 - Fair response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	3 - Good response	...	...	...	...	...	...	...	...	1	1	...	2	1	...	...
	4 - Incapacitation	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	Average rank	...	...	...	...	...	...	...	...	3.0	3.0	...	3.0	3.0	...	...
11	0 - No response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	1 - Poor response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	2 - Fair response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	3 - Good response	...	...	...	...	...	...	...	...	...	1	...	1	...	1	...
	4 - Incapacitation	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	Average rank	...	...	...	...	...	...	...	...	...	3.0	...	3.0	...	3.0	...
12	0 - No response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	1 - Poor response	...	...	...	...	...	...	1	...	...	...	...	...	...	...	...
	2 - Fair response	...	...	...	...	...	...	...	3	...	...	1	...	...	...	...
	3 - Good response	...	...	...	...	...	...	...	...	2	2	1	...	2	...	...
	4 - Incapacitation	...	...	...	...	...	...	...	...	...	...	...	2	...	...	...
	Average rank	...	...	...	...	...	...	1.0	2.0	3.0	3.0	2.5	4.0	3.0	...	...

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[1] Midpoint of a 1-inch interval

Table 1, continued

Length of fish (inches)1/	Type and rank of response	Voltage gradient (volts per inch)														
		0.26	0.32	0.37	0.42	0.48	0.53	0.58	0.64	0.68	0.74	0.80	0.84	0.90	0.95	1.0
13	0 - No response	...	1	...	...	...	...	...	...	...	...	...	...	...	...	...
	1 - Poor response	...	...	...	2	1	...	1	1	...	...	...	...	...	...	...
	2 - Fair response	...	...	...	...	...	...	1	1	...	...	...	...	...	...	...
	3 - Good response	...	...	...	...	...	1	1	...	4	1	2	4	...	...	...
	4 - Incapacitation	...	...	...	...	...	...	...	1	...	1	3	1	3	3	...
	Average rank	...	0.0	...	1.0	1.0	3.0	2.0	2.3	3.0	3.5	3.6	3.2	4.0	4.0	...
14	0 - No response	...	1	1	...	...	...	...	...	...	...	...	...	...	...	...
	1 - Poor response	...	...	...	1	2	3	3	...	...	...	2	...	...	...	...
	2 - Fair response	...	...	...	1	1	2	1	3	...	2	...	...	...	...	...
	3 - Good response	...	...	...	1	1	...	3	3	5	7	5	3	2	...	...
	4 - Incapacitation	...	...	...	...	...	...	1	...	1	3	2	2	4	1	2
	Average rank	...	0.0	0.0	2.0	1.8	1.4	2.2	2.5	3.2	3.0	2.8	3.4	3.6	4.0	4.0
15	0 - No response	...	...	1	1	1	...	...	...	...	...	...	...	...	...	...
	1 - Poor response	...	...	2	7	3	1	1	...	...	...	...	...	...	...	...
	2 - Fair response	...	...	...	1	2	2	...	4	1	...	...	...	...	...	...
	3 - Good response	...	...	...	...	1	1	4	2	13	3	1	5	1	1	...
	4 - Incapacitation	...	...	1	...	...	1	...	1	1	1	1	2	5	4	...
	Average rank	...	...	1.5	1.0	1.4	2.4	2.6	2.6	3.0	3.2	3.5	3.2	3.8	3.8	...
16	0 - No response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	1 - Poor response	...	...	...	1	1	...	2	...	...	...	...	...	...	...	...
	2 - Fair response	...	...	...	1	...	1	...	...	...	...	...	...	...	...	...
	3 - Good response	...	...	...	...	...	...	2	3	2	3	2	2	...	...	...
	4 - Incapacitation	...	...	...	...	...	2	1	1	...	...	...	...	...	...	...
	Average rank	...	...	...	1.5	1.0	3.3	2.4	3.2	3.0	3.0	3.0	3.0	...	...	...

1/ Midpoint of a 1-inch interval

Table 1, continued

Length of fish (inches)[1]	Type and rank of response	Voltage gradient (volts per inch)														
		0.26	0.32	0.37	0.42	0.48	0.53	0.58	0.64	0.68	0.74	0.80	0.84	0.90	0.95	1.0
17	0 - No response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	1 - Poor response	...	...	...	...	1	...	...	...	...	...	...	...	...	...	...
	2 - Fair response	...	...	...	...	1	...	...	...	...	...	...	...	...	...	...
	3 - Good response	...	...	...	...	1	1	...	...	...	1	1	...	...	...	...
	4 - Incapacitation	...	...	...	...	...	1	...	...	...	...	2	...	...	...	...
	Average rank	...	...	...	...	2.0	3.5	...	...	...	3.0	3.6	...	...	...	...
18	0 - No response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	1 - Poor response	...	1	...	...	...	...	...	...	...	...	...	...	...	...	...
	2 - Fair response	...	...	1	...	...	...	...	...	...	...	...	...	...	...	...
	3 - Good response	...	...	...	1	1	...	...	...	...	...	...	...	...	...	...
	4 - Incapacitation	...	...	...	...	...	1	...	...	...	...	...	...	...	...	...
	Average rank	...	1.0	2.0	3.0	3.0	4.0	...	...	...	...	...	...	...	...	...
19	0 - No response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	1 - Poor response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	2 - Fair response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	3 - Good response	...	...	...	1	1	1	...	...	...	...	...	...	...	...	...
	4 - Incapacitation	...	...	...	...	1	...	...	...	...	...	...	...	...	...	...
	Average rank	...	...	...	3.0	3.5	3.0	...	...	...	...	...	...	...	...	...
20	0 - No response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	1 - Poor response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	2 - Fair response	...	1	...	1	...	...	...	...	...	...	...	...	...	...	...
	3 - Good response	...	...	1	1	1	...	...	...	...	...	...	...	...	...	...
	4 - Incapacitation	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	Average rank	...	2.0	3.0	2.5	3.0	...	...	...	...	...	...	...	...	...	...

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[1] Midpoint of a 1-inch interval

Table 1, continued

Length of fish (inches)1/	Type and rank of response	Voltage gradient (volts per inch)														
		0.26	0.32	0.37	0.42	0.48	0.53	0.58	0.64	0.68	0.74	0.80	0.84	0.90	0.95	1.0
21	0 - No response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	1 - Poor response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	2 - Fair response	...	1	...	...	...	...	...	...	...	...	...	...	...	...	...
	3 - Good response	...	...	3	2	4	...	...	...	...	...	...	...	...	...	...
	4 - Incapacitation	...	...	...	...	...	1	...	...	...	...	...	...	...	...	...
	Average rank	...	2.0	3.0	3.0	3.0	4.0	...	...	...	...	...	...	...	...	...
22	0 - No response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	1 - Poor response	3	2	...	...	...	...	...	...	...	...	...	...	...	...	...
	2 - Fair response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	3 - Good response	...	4	2	2	1	...	...	...	...	...	...	...	...	...	...
	4 - Incapacitation	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	Average rank	1.0	2.3	3.0	3.0	3.0	...	...	...	...	...	...	...	...	...	...
23	0 - No response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	1 - Poor response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	2 - Fair response	1	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	3 - Good response	...	...	1	...	...	...	...	...	...	...	...	...	...	...	...
	4 - Incapacitation	...	...	...	...	3	...	...	...	...	...	...	...	...	...	...
	Average rank	2.0	...	3.0	...	4.0	...	...	...	...	...	...	...	...	...	...
24	0 - No response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	1 - Poor response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	2 - Fair response	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	3 - Good response	...	...	1	...	...	...	...	...	...	...	...	...	...	...	...
	4 - Incapacitation	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	Average rank	...	...	3.0	...	...	...	...	...	...	...	...	...	...	...	...

1/ Midpoint of a 1-inch interval

Table 2. Summary table of average rank of response and number of specimens involved
(Rainbow trout by inch-classes)

Length of fish (inches)[1]	Item	Voltage gradient (volts per inch)														
		0.26	0.32	0.37	0.42	0.48	0.53	0.58	0.64	0.68	0.74	0.80	0.84	0.90	0.95	1.0
9	Average rank	...	...	...	...	...	...	...	...	...	...	...	...	...	...	3.0
	Number of fish	...	...	...	...	...	...	...	...	...	...	...	...	...	...	1
10	Average rank	...	...	...	...	...	...	...	...	3.0	3.0	...	3.0	3.0	...	...
	Number of fish	...	...	...	...	...	...	...	...	1	1	...	2	1	...	...
11	Average rank	...	...	...	...	...	...	...	...	...	3.0	...	3.0	...	3.0	...
	Number of fish	...	...	...	...	...	...	...	...	...	1	...	1	...	1	...
12	Average rank	...	...	...	...	...	1.0	2.0	3.0	3.0	2.5	4.0	3.0	...	...	...
	Number of fish	...	...	...	...	...	1	3	2	2	2	2	2	...	...	...
13	Average rank	...	0.0	...	1.0	1.0	3.0	2.0	2.3	3.0	3.5	3.6	3.2	4.0	4.0	...
	Number of fish	...	1	...	2	1	1	3	3	4	2	5	5	3	3	...
14	Average rank	...	0.0	0.0	2.0	1.8	1.4	2.2	2.5	3.2	3.0	2.8	3.4	3.6	4.0	4.0
	Number of fish	...	1	1	3	4	5	8	6	6	12	9	5	6	1	2
15	Average rank	...	...	1.5	1.0	1.4	2.4	2.6	2.6	3.0	3.2	3.5	3.2	3.8	3.8	...
	Number of fish	...	...	4	9	7	5	5	7	15	4	2	7	6	5	...
16	Average rank	...	...	...	1.5	1.0	3.3	2.4	3.2	3.0	3.0	3.0	3.0	...	...	...
	Number of fish	...	...	...	2	1	3	5	4	2	3	2	2	...	...	...
17	Average rank	...	...	...	...	2.0	3.5	...	...	...	3.0	3.6	...	...	...	...
	Number of fish	...	...	...	...	3	2	...	...	...	1	3	...	...	...	...
18	Average rank	...	1.0	2.0	3.0	3.0	4.0	...	...	...	...	...	...	...	...	...
	Number of fish	...	1	1	1	1	1	...	...	...	...	...	...	...	...	...
19	Average rank	...	...	...	3.0	3.5	3.0	...	...	...	...	...	...	...	...	...
	Number of fish	...	...	...	1	2	1	...	...	...	...	...	...	...	...	...

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[1] Midpoint of a 1-inch interval

Table 2, continued

Length of fish (inches)[1/]	Item	Voltage gradient (volts per inch)														
		0.26	0.32	0.37	0.42	0.48	0.53	0.58	0.64	0.68	0.74	0.80	0.84	0.90	0.95	1.0
20	Average rank	...	2.0	3.0	2.5	3.0	...	...	...	...	...	...	...	...	...	...
	Number of fish	...	1	1	2	1	...	...	...	...	...	...	...	...	...	...
21	Average rank	...	2.0	3.0	3.0	3.0	4.0	...	...	...	...	...	...	...	...	...
	Number of fish	...	1	3	2	4	1	...	...	...	...	...	...	...	...	...
22	Average rank	1.0	2.3	3.0	3.0	3.0	...	...	...	...	...	...	...	...	...	...
	Number of fish	3	6	2	2	1	...	...	...	...	...	...	...	...	...	...
23	Average rank	2.0	...	3.0	...	4.0	...	...	...	...	...	...	...	...	...	...
	Number of fish	1	...	1	...	3	...	...	...	...	...	...	...	...	...	...
24	Average rank	...	...	3.0	...	...	...	...	...	...	...	...	...	...	...	...
	Number of fish	...	...	1	...	...	...	...	...	...	...	...	...	...	...	...

[1/] Midpoint of a 1-inch interval

The tests demonstrated that it was not only possible to stimulate the desired movement of rainbow trout in the field, but also that the fish could be made to enter an enclosure. Each rainbow trout was tested individually. The first 21 experiments were conducted with the device installed as shown in Figure 3. In 11 experiments the fish were allowed to swim unmolested into the area between the electrodes before the power was applied. Of the 11 rainbow trout subjected to this procedure, 8 entered the trap and 3 were electronarcotized. One of the 3 turned over enroute to the trap and the other 2 displayed a galvanotaxic response similar to that classified during the laboratory tests as "overcontrol". The location of the fish in relation to the electrodes made no detectable difference in results. It was found also that as long as the power remained on, the fish did not, or could not, leave the trap. The polarity was reversed in a few of the tests after the trout had entered the trap. On each occasion, the test animals immediately left the trap and went to the opposite electrode. This procedure could be repeated three or four times with an active fish before exhaustion resulted in its being carried out of the electrical field by the stream flow.

The remaining 10 rainbow trout were released individually well below the electrode array with the power applied constantly in an attempt to determine the reactions of the fish upon contact with the extremity of the electrical field. Of the 10 trout, 4 were successfully drawn to the anode, but only after an appreciable increase in the electrode voltage. The rest invariably turned back downstream upon encountering the weak fringe of the electrical field.

Thirteen of the 34 rainbow trout were subjected to tests with a different electrode array. The original electrodes were replaced by two pieces of 2-inch diameter aluminum tubing, suspended vertically, spaced 11 feet apart, and immersed to a depth of 6 inches. Results with this arrangement were poor even with an electrode voltage as high as 230 volts. At this voltage level, power consumption was less than that of the original array with an electrode voltage of 90 (115 watts as compared to 135 watts). The above tests with the extremely small electrodes were conducted to determine the influence of immersed electrode area on the voltage gradient as portrayed by the reactions of the fish. Other studies aimed at development of an electrical sea lamprey control structure included tests to determine the relative efficiency of electrodes of various sizes, shapes, and materials.[6] These studies demonstrated that electrode size does effect voltage gradient. McMillan (1928) also conducted an extensive investigation of the same nature.

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[6] See footnote 2.

Laboratory tests on other species.--During the first part of the study a few black bullheads (*Ameiurus m. melas*), northern pike (*Esox lucius*), and yellow perch (*Perca flavescens*) were available. Tests with these fish were made at water temperatures of 36° to 39° F., and at a time when the experimental conditions producing the best results with trout had not been determined. The bullheads were inactive and could not be stimulated into appreciable movement. They gave little outward sign of discomfort at voltage gradients up to and including those at which they were electronarcotized.

The results obtained with northern pike indicated they would respond favorably if subjected to the right combination of conditions.

The small number of yellow perch restricted the number of tests with this species. In a few trials, however, the desired response was obtained. The manner in which the perch responded was most unlike that of the trout. In contrast to the rather violent and explosive movement of the trout, movement of the yellow perch toward the anode was slow, almost natural, yet persistent.

Other laboratory tests.--The only other type of current tested that yielded promising results was half-wave, rectified, 60 cycle AC. It was applied continuously and also pulsed at duty cycles of 0.25 and 0.66. This type of current caused involuntary movement of brook trout toward the positive electrode, but the results were not as satisfactory as those obtained with filtered DC at a duty cycle of 0.66. Limitations in time and equipment prohibited investigation of other than essentially square wave shapes. Studies of other wave shapes are desirable since it has been shown by Groody, Loukaskkin, and Grant (1952) that a somewhat triangular wave was highly effective in controlling the movement of Pacific sardines (*Sardinops caerulea*). The work of Kreutzer in Germany (Houston, 1949) seems to be based on the use of a somewhat triangular-shaped wave.

Prospects and problems in the application of an electrical leading device

Laboratory tests demonstrated that rainbow trout and brook trout, subjected to an appropriate electrical stimulus, swam involuntarily and persistently to the anode or positive electrode. The most satisfactory results were obtained with pulsated direct current of an essentially square wave shape at a duty cycle of 0.66 and a rate or frequency of 3 pulses per second. Direct current of this type can be used also under field conditions to assemble white suckers and rainbow trout at the anode or to cause them to enter a properly designed enclosure.

Water temperature may be a factor contributing to negative results obtained with white suckers in the laboratory under theoretically ideal conditions. The favorable results in the field were obtained at water temperatures of 75° to 78° F. whereas the water in the laboratory ranged from 36° to 39° F. No tests were made at intermediate water temperatures. It appears probable that at low temperatures the reduced metabolism of the white sucker limits galvanotaxic response. However, no visible difference was observed in the reactions of rainbow trout at various temperatures between 36° and 63° F.

The experiments show that the device is selective as to size, and this factor alone restricts its use as a collecting device. Voltage gradients effective for leading rainbow trout vary inversely with the length of the fish. For each size class of rainbow trout, the leading response can be obtained only from voltage gradients that fall within a specific range. The determination of the actual limits of this range for each group is complicated by the variability of the response displayed by test animals of similar lengths. A voltage gradient applied to stimulate the desired movement in large fish would not cause a similar movement in small fish nor be harmful to them. On the other hand, a voltage gradient sufficient to control small fish would narcotize, injure, or even kill any large fish in the electrical field.

Of all the fish used in this study, only 7 brook trout suffered injury or death directly attributable to exposure to pulsated direct current. Of these, 6 were killed by a severe dislocation of several vertebrae just anterior to the dorsal fin. In some of these fish, the displacement was such that the vertebrae were separated from the ribs. Holmes (1948) and Hauck (1949) described similar injuries to rainbow trout and other species subjected to alternating current. The remaining brook trout suffered severe internal hemorrhage and had a large quantity of blood present in the air bladder.

The field tests demonstrated that the leading device could be operated successfully in a stream and indicated the desirability of further investigation. A continued study should be directed toward the determination and evaluation of factors which prevent the attainment of uniformity of the voltage gradient. The field tests demonstrated that the area of the immersed electrode and the ratio of stream bottom to water resistivity are factors of prime importance. The maximum distance permissible between electrodes is determined by the above factors. The voltage gradient, in turn, will vary inversely as the electrode spacing. In theory, the distance between the electrodes in a completely insulated tank can be increased indefinitely, as long as the peak input voltage is increased proportionately, without changing the uniformity or the value of the voltage gradient.

Water resistivity changes with temperature (McMillan, 1928) and with changes in amounts of dissolved or suspended materials. The maximum drop in electric current (21 percent) in the laboratory test tank during the course of experimentation was observed following a storm which caused the intake water to become very turbid. Changes in water resistivity of this type in the field would not necessarily change the value or uniformity of a voltage gradient. They could conceivably bring about sufficient change in the conditions that control the response of the fish as to require readjustment of the voltage gradient by a change in the input voltage. For example, McMillan (1928) has shown that a voltage gradient of 0.27 volt per inch will paralyze a 3.1-inch chinook salmon fry (Oncorhynchus tshawytscha) in sea water having a low resistivity while 1.23 volts were necessary to produce the same effect in fresh water of high resistivity. It is believed the change in the response of the fish is due to a change in the ratio of water resistivity to body resistivity of the fish and a consequent alteration of the voltage developed across the length of the fish. However, this factor would be a matter of concern only when changes of water resistivity are large and rapid because the leading response on the part of the fish is attainable over a fairly wide range in voltage gradient.

More important than water resistivity per se is the ratio of water resistivity to bottom resistivity. The bottoms of the two experimental streams were roughly 2 to 3 times more resistant to the flow of electrical current than was the water. The higher the ratio of bottom to water resistivity the better conditions are for the establishment of a uniform voltage gradient. Where the bottom is more conductive than the water, it is doubtful whether a voltage gradient of usable character between electrodes spaced more than a few feet apart could be established without the use of artificial insulating materials on the stream bottom.

This study has revealed several factors which appear to be obstacles to the practical use of pulsed direct current as an effective means of leading desirable fish away from sea lamprey control structures. Size selectivity is without doubt the major limiting factor. The highly diverse physical conditions encountered in streams over a large area also offer a number of obstacles. Still another problem is presented by the possibility that a large number of fish may turn away upon encountering the fringe of the electric field as was indicated by the tests in the Little Ocqueoc River. It may be possible to overcome this latter problem by intermittent operation on a critically times basis, or it may be that the persistence of upstream migrants is great enough to result in penetration of the electrical field. These and comparable problems may be solved by further study.

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