THESIS

ELECTROFISHING AS APPLIED TO COLORADO WATERS

Submitted by
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for the Degree of Master of Science
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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY FREDERICK WILLETT JACKSON ENTITLED ELECTROFISHING AS APPLIED TO COLORADO WATERS BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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Permission to publish this report or any part of it must be obtained from the Dean of the Graduate School.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES--Continued

Chapter I

INTRODUCTION

While the past two thousand years have seen great improvements in the equipment of most fields of endeavor, the professional fisherman is still using tools similar to those in use during the pre-Christian era. Certainly there have been few changes in the gill net and seine, and these tools are still the ones most widely used for catching fish in quantity. During the past decade, however, there has been an ever expanding application of an electrical method of fishing. This is most aptly termed electrofishing, a name probably first applied by the Germans who have pioneered the field.

In the 1920's many data appeared in German physiological journals on the effects of various types of electric current on fish and other water animals. This information was subsequently applied to the development of practical electrofishing equipment, and in 1933 Schaeperclaus (1933) briefly describes such an application to the German carp farming industry. About the same time, Russian fishery workers appear to have seriously considered the practicability of this electrical technique for their fresh-water commercial fishing industry (Smetanin, 1933).

Although in 1928 McMillan (1928), from investigations relative to the development of effective electrical

1 2 fish barriers, showed, in detail, the interrelations of electrical fields, water, and fish, little further application of electricity was made to American fishery work until 1940. At that time, D. C. Haskell (1940) of the New York Conservation Department, described the construction and operation of an electrofishing unit designed for stream work. Since then, except for the years during World War II, there has been an ever increasing use of the technique in the United States and Canada. Many improvements have been made on the original forms of equipment, and much has been learned about the effects and limitations of electricity for fish shocking. Among all of the more recent developments, the work of Haskell appears to be outstanding, and it has been our good fortune to find the author of these investigations generous with his information and helpful relative to our own problems.

It has become apparent, both from experience and the literature that much misunderstanding has existed concerning the potentials and limitations of electrofishing. During many electrofishing operations in Colorado and Wyoming it has been possible for us to observe the efficiency and effectiveness of various forms of equipment; it has become necessary to recognize the electrical importance of the widely varying concentrations of dissolved materials in the natural waters of this region; and it has seemed increasingly more essential to study all physiological effects and particularly those of an injurious or lethal nature. It is our hope that the results of our studies on these phases of electrofishing will assist in a more generally efficient utilization and understanding of its application.

Problem

How may the electrofishing technique be used most efficiently with a minimum of physical damage to game fish species?

Problem analysis. -- The problem has been analyzed into the following questions:

1. What type of equipment may be used most efficiently and with the greatest fishing effectiveness?
2. In what way and to what extent does the wide range of natural water conductivity encountered in Colorado restrict electrofishing effectiveness?
3. How serious are some of the physical and physiological effects of electric current, as encountered in electrofishing operations, on fish and to what extent are these injurious or lethal?

Delimitations. -- Most of the field studies were limited to the more accessible waters of the northeastern part of the state. As the greater part of Colorado's stream fishery is confined to the foothill and mountain areas, most investigations were made on representative streams of these areas. In as much as trout species form the principal game-fish of such streams, both laboratory and field investigations emphasized effects relative to these species.

All laboratory tests were made within the scope of available time and equipment and as relative to practical application.

Definition of terms. -- Electrofishing is the term herein used to designate the mass capture of fish by means of electrical currents introduced into the water.

Voltage Gradient refers to the voltage drop, or difference in potential, along a specific length of conductor. In this paper the reference is usually to the drop in volts per linear inch of water.

Lines of Current Flow are diagramatic lines representing the passage of current in an electrical field.

Lines of Equipotential are diagramatic lines transecting those points in an electrical field at which the potential, or voltage, is uniform. They intersect the lines of current flow at right angles.

Pulsed Current is the term used to describe a galvanic current interrupted at regular intervals by mechanical or electronic means.

Water Conductivity refers to that property of water which permits the conduction of electric current, whereas Water Resistivity refers to that property of water which produces resistance to the passage of electric current.

Specific Resistance refers to the resistance in ohms per cubic centimeter of water.

Versene is the trade name applied to a versenate method of determining the total hardness of water. The Versene Hard Water Testing Kit is a product of the Bersworth Chemical Company, Framingham, Massachusetts.

Chapter II

EVALUATIONS OF ELECTROFISHING EQUIPMENT AND TECHNIQUES

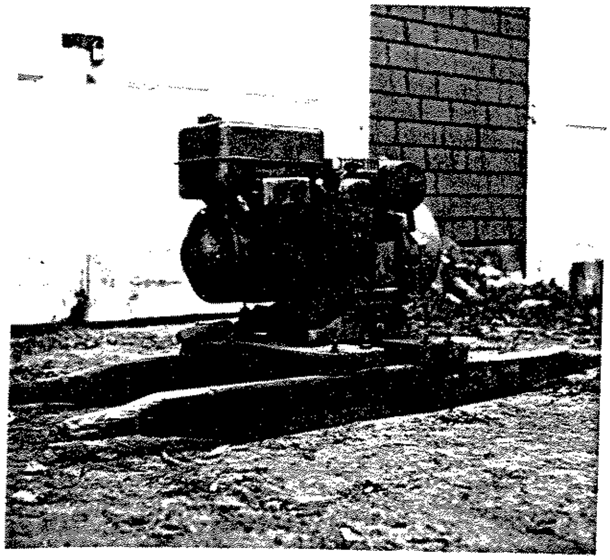
Generators

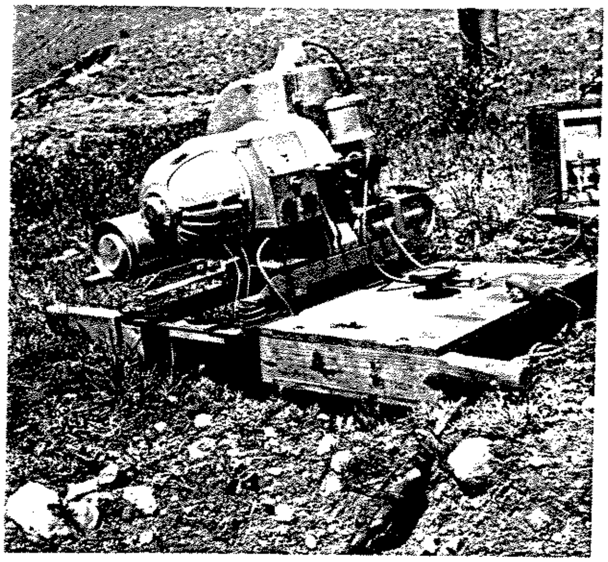
The principal part of any electrofishing unit is the power source, usually in the form of a gasoline driven generator producing either alternating or direct current. Although the general fishing technique for both currents is very similar, the actual shocking effects of each differ considerably (Kraus and Reiffenstuhl, 1933) and hence each is particularly suited to certain situations and problems.

As the respective physiological aspects are covered elsewhere in this paper, a statement of the general effects of alternating and direct currents will suffice here. Alternating current immobilizes the fish while they are in the electrical field, (Scheminzky, 1933) and, if the time of immobilization is sufficient, leaves them helpless for a short time after their removal from the field. During this time many fish are easily picked up in dip nets. Direct current has a galvanotactic effect by which a fish is oriented with its head toward an electrode of positive polarity. If, in this situation, the voltage gradient, or drop, from head to tail is not too great, the fish is still able to move and swim toward the positive electrode. Such forced movement toward the anode allows easy capture of fish led from otherwise inaccessible areas. Subjection of a fish to direct current, either of a sufficiently high voltage gradient or for a prolonged period of time, however, produces a narcosis in which the fish is no longer able to move (Schmeninzky, 1936).

Although most of the generators used for electrofishing are classified as portable machines, they are portable only in that they can be moved. Usually weights will range between 75 and 175 pounds, depending on the generator output and the amount of additional incorporated equipment.

Our alternating current machine is an Onan Electric Plant Model No. 05AE-2M, rated at 230 volts, 2.17 amperes, and 60 cycles (Figure 1). For current control of this generator, we use a detachable variable transformer which can be carried separately. Stretcher type carrying handles form the only modification to the machine as manufactured, and its weight, with handles, is 148 pounds. Within its power limitations, this generator has proved to be very serviceable, although the engine is extremely difficult to start in cold weather. A readily adjustable throttle makes it possible to greatly increase the engine revolutions per minute, which in turn produce a considerable increase in the number of cycles of the generator and its subsequent voltage output. It





should be emphasized, however, that prolonged generator speed increases are not to be recommended as they cannot be maintained without danger of damage to the unit.

For direct current we use a Homelite, Model 24D230-1, rated at 230 volts and 10.9 amperes. This machine, likewise, is mounted on stretcher type carrying handles, to which are attached a field rheostat and circuit breaker panel (Figure 2). While the Homelite weighs 160 pounds it has a lower center of gravity and, because of this and better weight distribution on the handles, does not seem more difficult to carry. The engine is easily started regardless of weather conditions, but cannot be speeded up to produce voltage output above the 230 volt rating.

We have substantially established that both of these units have good and bad features, and that each has a greater effectiveness for particular stream conditions. Slow moving waters having much cover in the form of snags, dams, and overhanging banks and brush are very effectively worked with the D. C. unit which has the advantage of being able to draw the fish out from such cover, and, in the case of some beaver pond sections, to bring the fish to the surface for easy capture despite considerable turbidity and depth. However, in waters having fairly rapid flow, it has been observed that the fish, while still able to swim in the D. C. field, could not do so sufficiently well to withstand the force of the water, were removed from electrical influence, and quickly recovered their normal faculties. Under such conditions many fish were observed to be lost.

It was also discovered that the D. C. machine lacked sufficient voltage output to produce an effective electrical field in waters of high resistivity. In such waters the only fish shocked were those that were accidentally brought into the high voltage area directly adjacent to an electrode. In both these situations the A. C. was found to be advantageous from two standpoints. Firstly, its immobilizing effects are such that recovery is not usually instantaneous upon removal from the field, thus providing a longer time in which to capture the fish. Secondly, the voltage differentials represented by peak voltage values and variable generator speeds increase the strength and effectiveness of the electrical field. Relative to electrofishing, an important consideration in making any comparison of alternating and direct currents, having equal source or "name plate" voltages is the fact that readings of direct current voltage, which is noncyclic, represent a constant voltage, while readings of alternating current, because of its cyclic nature, represent effective voltages, with peaks that actually rise considerably above the "name plate" or rated voltage. For example, the peak values of a rated 230 volt alternating current generator will actually be about 325 volts ($230 \times \sqrt{2}$).

It is extremely difficult to make valid comparisons of the respective efficiencies of the two types of current under field conditions. An ideal method is to block off two similar sections of stream, determine the population of fish in each section and compare percentages of the total population taken by each current on each shocking run. In most western streams it is impossible to retain temporary blocks, such as nets, for a sufficient time to make such a study. In lieu of this it appears that an estimation of efficiency may be made based on the percentage of recovery of marked fish from an unblocked stream section, where beaver dams or shallow riffles provide quite effective barriers to fish attempting to move from the sampling area. Utilizing such natural barriers, a series of comparisons was run on similar sections of the North Fork of the Michigan River. Two pond sections were stream channel beaver ponds. Both ponds were about 200 feet long and had heavily silted bottoms and generally similar configurations. Two stream sections were each about 250 feet long, and both had an average width of eleven feet, an average depth of 0.8 feet, a velocity of about 0.7 feet per second. In all of these sections, the brook trout, _Salvelinus fontinalis_, was the predominant species, with brown trout, _Salmo_ trutta, and rainbow trout, Salmo gairdnerii, being present in relatively small numbers. No other species of fish were observed. Samples of the fish population of each section were captured by shocking. The original samples from all sections were marked for identification with distinctive fin clips and released in the central part of the section. Approximately 24 hours after initial sampling, each section was reshocked and the number or recaptures recorded. Both the original sample and the recaptures of each section were taken with the same type of electrical current (Table 1). A statistical test of the differences between the total percentages of fish recovered with alternating and direct current electrofishing equipment was run, using the significance of difference between proportions (Arkin and Colton, 1939). There was no significant difference between the total percentages of recovery for either type of current in the pond or stream sections respectively, but there is indication of a higher efficiency for both in the stream section. The difference between the recovery percentages for pond and stream shocked with alternating current does not prove to be of high significance, but for direct current the difference lies above the 95 percent level of significance.

One additional comparison was attempted. Two 400 foot stream sections were sampled in the above

Table 1.--TOTAL NUMBER AND PERCENTAGE OF FISH RECOVERED WITH 230 VOLT ALTERNATING AND DIRECT CURRENT SHOCKERS ON POND AND STREAM SECTIONS OF THE NORTH FORK, MICHIGAN RIVER.

	Pond Sections								Stream Sections*							
	Alternating Current				Direct Current				Alternating Current				Direct Current			
	Brk.	Rb.	Br.	Total	Brk.	Rb.	Br.	Total	Brk.	Rb.	Br.	Total	Brk.	Rb.	Br.	Total
Number of marked fish present	15	1	--	16	61	--	--	61	21	--	1	22	33	1	3	37
Number of marked fish recovered	8	1	--	9	34	--	--	34	16	--	1	17	27	1	2	30
Percentage recovery	55.3	100		56.3	55.7			55.7	76.2		100	77.3	81.8	100	66.6	81.1

* average width 11 feet
average depth 0.8 feet
velocity 0.7 feet per second

Brk. -- Brook trout
Rb. -- Rainbow trout
Br. -- Brown trout

7 described manner. The sections appeared similar in all respects, including average width and depth, except that the section worked with direct current had a water velocity of about 1.7 feet while the alternating current section had only 0.9 feet per second. The percentage of recovery for direct current was 8.3 and for alternating current 46.4, and the difference between these values, lying above the 95 percent level of significance, gives an indication of the important relationship of the force of the water to shocking efficiency. While we have been able to show little difference in overall efficiency between alternating and direct currents, it is interesting to note that Pratt (1952), from similar trials, reported higher efficiency for direct current. It may be of importance that, in his comparisons, the alternating current unit was rated at 110 volts and 500 watts while the direct current was supplied by a 230 volt, 2500 watt machine. More recent comparisons in New York State (Webster, et al, 1955) were made with alternating and direct current machines of identical voltage and wattage ratings, and these indicated a higher efficiency for alternating current.

Whatever the type of current used there is one consideration which appears to have particular importance in many areas of the Rocky Mountain region. For greatest practicability a generator must have a sufficiently high voltage and amperage rating to allow its use in the widest possible range of water resistivities. In the past very little has been known about the probable power requirements for shocking operations, and it has been a common practice to completely overlook the fact that a machine of low voltage and amperage capacity will have very limited application. We have found that the range of Colorado's water resistivity is such that none of the machines, with which we have had experience, will cover it. At present, the 230 volt, 10-11 ampere generators appear to be the highest rated available in the United States for practical electrofishing purposes, and they are satisfactory for a fair range of water conditions. Lower voltage machines will prove very ineffective in many of our mountain headwaters, and units with appreciably lower amperage capacity will have little value in the more saline waters of this area.

While alternating and direct currents have had wide application in American fisheries work, comparatively little field application has been made of pulsed or interrupted currents. In Germany, where electrofishing appears to have reached a relatively high degree of development, battery operated units producing pulsed current have proven to be quite effective (Meyer, 1951). At least two German companies are commercially manufacturing electrofishing equipment, and through recent correspondence with one of these we have obtained information on a gasoline driven generating unit that will produce pulsed current. As yet, however, we have been unable to learn by what method the pulsations are produced on this and other German machines.

Standard physiological experiments show that electric current effects a nerve stimulus upon each closure and upon each opening of an electrical circuit. Further, in the case of galvanic current, the response is the greater for circuit closure (Zoethout and Tuttle, 1946:91-92). Pulsed current, as used for electrofishing, is a galvanic current having a constant rate of such make and break interruptions per second. In order for it to produce maximum fishing effectiveness, certain ratios of on and off periods as well as pulse frequencies appear to be necessary. According to Haskell, et al, (1954) pulse duration should be long enough to reduce voluntary motion without producing complete narcotization. Under such conditions the fish show the usual galvanotactic response and, in addition, an involuntary swimming motion resulting from the pulse stimulus. An optimum relationship appears to exist at a rate of one square pulse per second with a peak of 133 volts maintained for 0.8 seconds, (Haskell and Adelman, 1955). The Colorado A and M Department of Electrical Engineering has designed a variable interruptor which, with a 230 volt alternating current generator, can produce either rapidly pulsed or steady direct current. During the preliminary tests of this device, the reactions of the fish have been erratic and otherwise very similar to those described by Haskell for rapidly pulsed current. If this compact unit can be improved to produce a more effective pulsed current, it will be a very practical addition to electrofishing equipment. With one generator and little additional expense and weight it will be possible to have alternating, steady direct, and pulsed direct currents.

From our brief discussion of the bulk and weight of gasoline driven generators, it is obvious that these units are impractical for use in relatively inaccessible waters. For this phase of electrofishing, some form of battery operated equipment appears to be the answer. We have mentioned that the Germans have developed battery operated shocking units, but, although some of these are relatively small and compact, their design does not appear to be well suited to extensive portage. We have made a number of trials with an aircraft dynamotor energized by a six or twelve volt storage battery. The dynamotor is a Ballentine, Type No. 530D3 CB, manufactured by the Russel Electric Co. of Chicago. It draws 21 amperes on a six volt battery and eleven amperes on a twelve volt battery and puts out 500 volts and 0.16 amperes of direct current. Both dynamotor and battery are

1 attached to a wooden frame which in turn is lashed to a U. S. Army packboard (Figure 3). The unit's portability depends on the weight of the battery. Without battery the packboard and dynamotor together weigh about 40 pounds; the addition of a twelve volt aircraft battery raises the total weight to 63 pounds, a readily manageable load. As the aircraft battery that we have used has a 25 ampere-hour rating and as the dynamotor draws 11 amperes at 12 volts, the maximum operational time is about 2 hours. For a charge of longer duration we have tried both standard and heavy duty six volt automobile batteries. These range from about 100 ampere hours for the standard to about 130 for the heavy duty and extend the possible constant operational time to between four and six hours. The "life" of any of these batteries can be considerably lengthened by a switch controlling the battery circuit so as to run the dynamotor only when needed. Although the use of automobile batteries substantially lengthens the operational life of the unit, their weight of 45 pounds so increases the pack load that it becomes back-breaking and ungainly.

An additional limitation lies in the amperage capacity of the dynamotor itself. It has been found that, when used with our paddle-type electrodes for waters ranging below 30,000 ohms per cubic centimeter in specific resistance, the dynamotor rapidly becomes overheated.

2
12

With electrodes placed six feet apart in the stream, we have recorded a water resistance of about 2,000 ohms in a stream having the unusually high specific resistance of about 50,000 ohms per cubic centimeter. Applying Ohm's law to the ratings of the dynamotor, it will be seen that a resistance of over 3,000 ohms is necessary to prevent an overload of the machine. From these data, it would appear that any conceivable natural water conditions will cause eventual overheating.

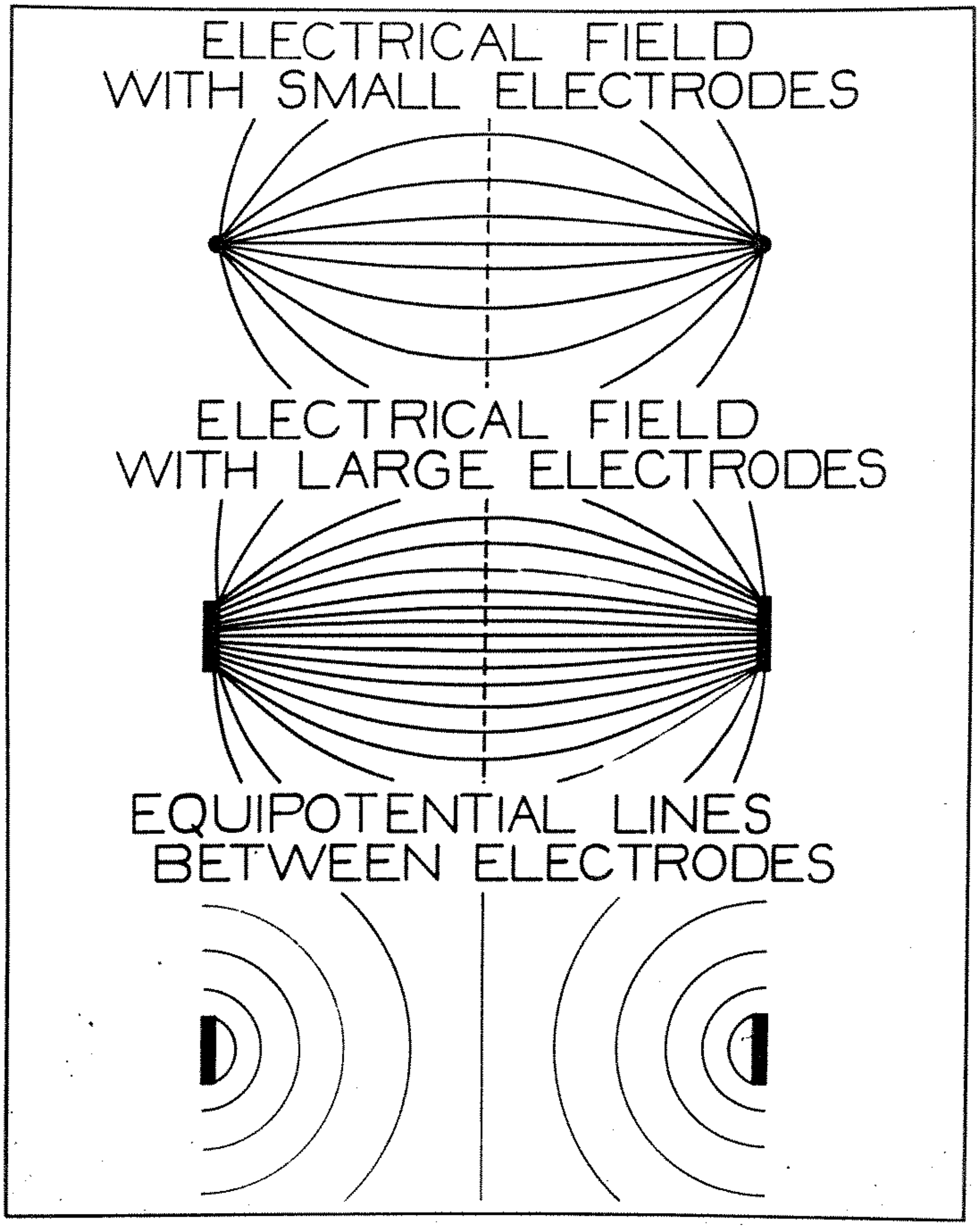
The Colorado A and M Electrical Engineering department has constructed a very light and compact vibrator-transformer unit patterned after those described by Haskell, <u>et al</u>, (1954). The vibrator transforms the direct current of a storage battery to alternating current and a pair of transformers changes the low voltage, high amperage current to high voltage and low amperage. With the addition of a rectifier, the alternating current may be converted to high voltage direct current. It has not as yet been possible to obtain the parts necessary to provide the latitude of operation reported by Haskell, and the present 100 volt output has not proven too effective in trials made in water with a specific resistance of about 15,000 ohms per cubic centimeter. Eventual modification will raise both the voltage output and current capacity, and these improvements, together with its light weight and reduced battery drain, should make this unit very effective for small, inaccessible, mountain streams.

Electrodes

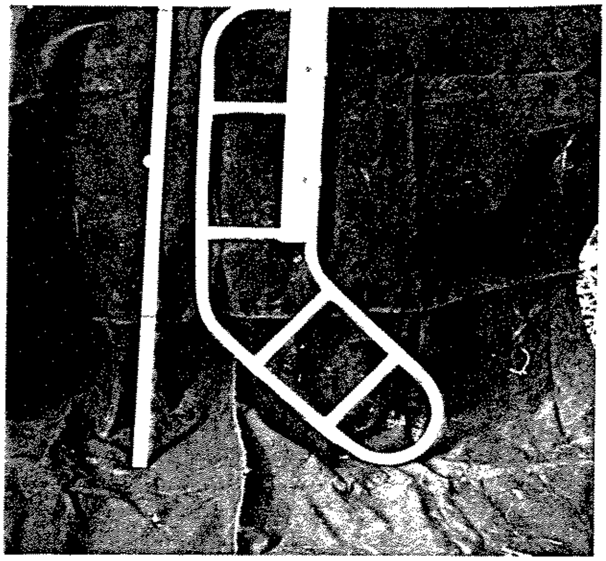
The electrodes, by which the electric current is introduced into the water, are almost as important to electrofishing as the current source. When an electrical circuit includes a conductor of constant diameter, such as a cable, the voltage gradient remains uniform along the length of that conductor. The electrical field between two electrodes in a stream, however, presents an entirely different situation. Here the conductor, the stream water, has a diameter restricted only by the dimensions of the stream bed. The lines of electrical current-flow diverge from each of the electrodes so that while the voltage gradient will measure several volts near an electrode, it may be a fraction of one volt at a point midway between electrodes. Two bare copper wires, attached to a current source and immersed in a stream will produce an electrical field. However, much of the effectiveness of an electrical field in water is directly related to the area of conducting surface of the electrodes (McMillan, 1928) and, if the conducting surface is small, the lines of current flow are concentrated at the electrode and diverge very rapidly, so that they may

4 be widely dispersed midway between the electrodes (Figure 4). In this situation there is an extremely high voltage gradient at the electrodes and a very low one half way between them. Electrodes with greater conducting surface will reduce the voltage gradient at the electrodes. At the same time the voltage gradient at the midway point will be appreciably higher, because the lines of flow are more nearly parallel throughout the entire length of the intermediate water (Figure 5). This can be readily demonstrated in stream or laboratory with a vacuum-tube voltmeter and a voltage gradient probe. We have been able to produce an almost completely uniform voltage gradient between electrodes set at either end of an aquarium and having the aquarium end-dimensions. On the other hand, electrodes of copper tubing similarly placed in the same volume of water, produce a typically spindle-shaped field. The rapidity of divergence of the lines of flow will, of course, vary considerably in different waters, depending on their resistivity. We have observed that in waters of extremely high specific resistance, 30,000 ohms per cubic centimeter, current conduction requires a field of much greater width than is necessary in waters of a more moderate specific resistance of about 10,000 ohms per cubic centimeter.

From the foregoing discussion one must surmise that, within the physical limitations of the generator


ELECTRICAL FIELD
WITH SMALL ELECTRODES
ELECTRICAL FIELD
WITH LARGE ELECTRODES
EQUIPOTENTIAL LINES
BETWEEN ELECTRODES

and the operating personnel, the greater the electrode surface, the more effective the electrical field produced. We have had some experience with electrodes made of short pieces of heavy copper wire or 1/4 inch copper tubing. These have proven to be of very limited effectiveness, due to small and concentrated surface areas. While electrodes of design similar to those described by Shetter (1947) have been very satisfactory, we felt that a combination of the elongated-rectangular and foot-shaped designs would give us an electrode that would always have a maximum conduction surface in the water. The final product, shown in Figures 7 and 8, is constructed of 1/2 inch copper tubing bent to the general conformation of a sock-stretcher and clamped into a six foot wooden handle. The cross braces, of the same tubing, are soldered into place, and the section fitting into the handle is reinforced with a piece of steel rod. The cables to the copper are taped to the full length of the handles. Each electrode is about 19 inches in length, five inches in width, and each has about 98 square inches of surface area. This area is about ten times as great as that for the short pieces of tubing or wire, and actual measurements have shown those bigger electrodes, to have a field of considerably improved effectiveness. We have found this design to offer little resistance to water current, and because of the relatively simple form, to be

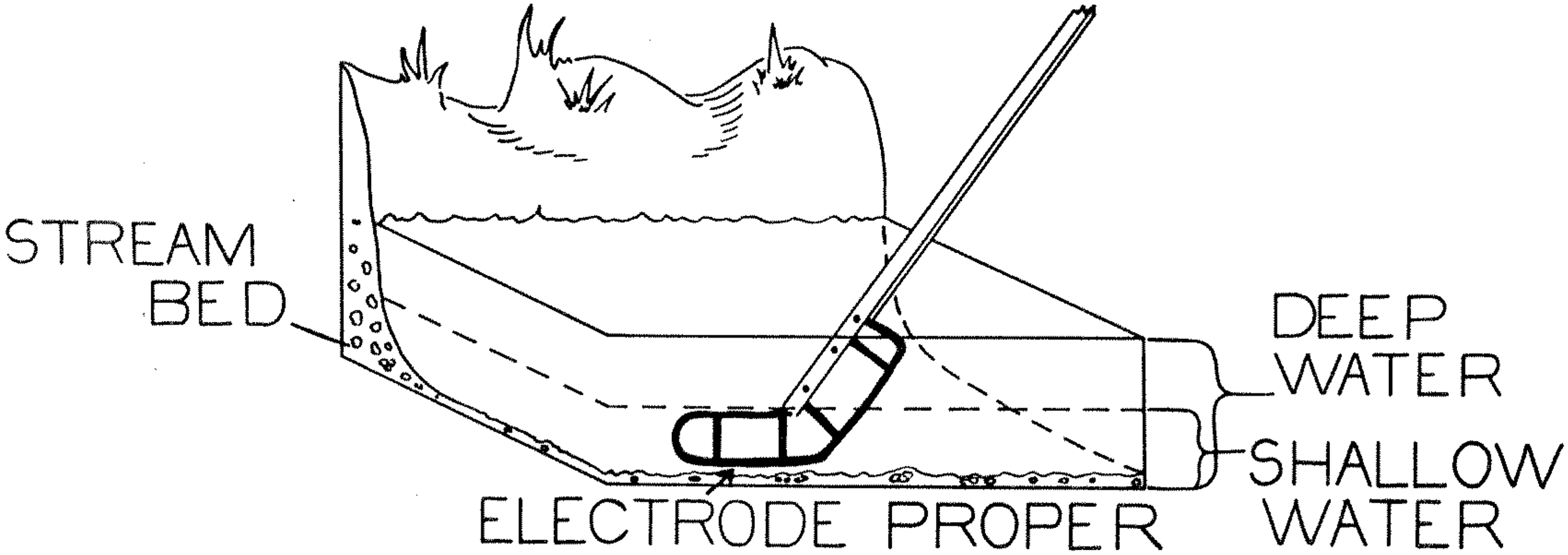


16 excellent for probing dead-falls, etc., without danger of snagging. To further increase the surface area for work in waters of extremely low conductivity, a sheath of 1/8th inch mesh hardware cloth was soldered to the tubing. While this modification has provided an even more effective field, it has also substantially increased the weight and resistance to stream flow. Handles were made of single pieces of 1 1/2 x 1 inch pine covered with three coats of marine varnish. A year and a half of hard use have proven the overall construction of these electrodes to be very satisfactory.

Using the same general sock-stretcher design, it might be possible to strengthen and greatly simplify the construction by making each electrode, including the handle, from a single piece of 1/2 inch or 3/4 inch diameter electrical metallic tubing such as is manufactured by the General Electric Corporation. The cross braces could be welded on, and the handle could be either completely taped or fitted into a section of rubber pipe or hose.

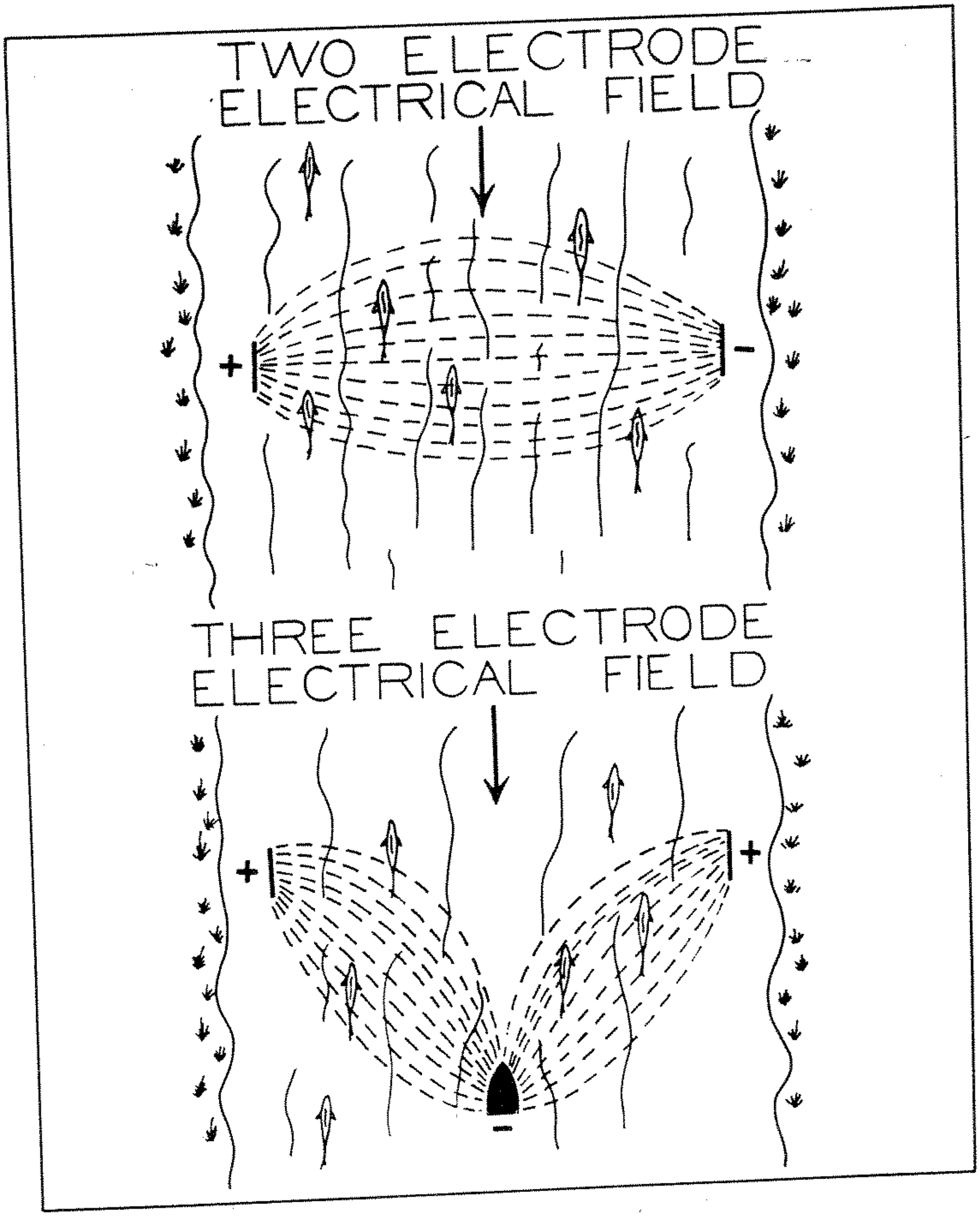
For many operations we have found the use of two electrodes to be entirely satisfactory, but in some situations we have successfully used a third electrode made of a short, screen covered, section of two-by-four and towed, with a rope halter, by the probe handlers. Beside increasing the effective length of the operating

PADDLE-TYPE ELECTRODE
IN STREAM



span, this system has proven to be one of considerable value with direct current units as it permits both probes to be used as positive poles while the third electrode serves as a negative. It has an additional advantage in that it improves the orientation of the electrical field.

As we have mentioned, an electrical field is characterized by lines of flow between electrodes. Along imaginary lines perpendicularly intersecting the lines of flow, there is no voltage drop or difference in potential, and such intersects are termed lines of equipotential. Their relation to a pair of electrodes in water is schematically shown in Figure 6. For effective shocking the long axis of a fish's body should closely parallel the lines of flow and cross the lines of equipotential. In this position, a maximum head-to-tail difference in potential is produced. If the long axis of a fish's body is parallel to the equipotential lines, there is almost no difference in potential across the body, and it sustains no shock. In laboratory experiments we have been able to observe demonstrations of this relationship on two to five-inch carp, Cyprinus carpio. Repeatedly, specimens placed in a plastic screen envelope and oriented parallel to the lines of current flow and across the lines of equipotential would become rigid upon application of a voltage gradient of about 1,000 volts per inch. Upon cessation of shock the fish would usually die within a


TWO ELECTRODE ELECTRICAL FIELD
+
-
THREE ELECTRODE ELECTRICAL FIELD
+
+
-

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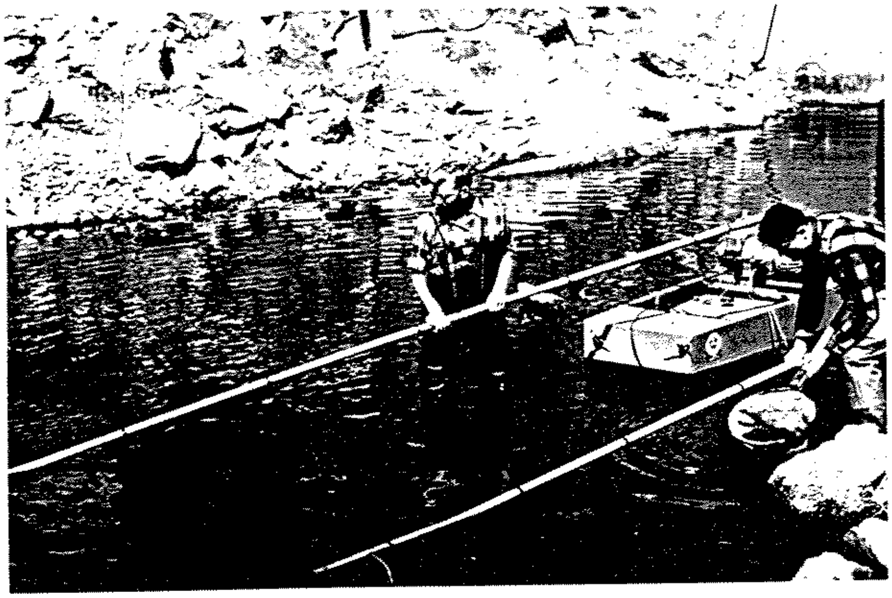
few hours. Others, similarly held but placed across the lines of flow and parallel to lines of equipotential never stopped breathing during the same voltage application and usually showed no subsequent signs of injury.

Usually in stream shocking the electrode handlers move up or down stream near each bank, so that the lines of electrical current flow are at right angles to the stream flow and, also at right angles to the most probable position of the fish (Figure 9). Thus the fish are parallel to the lines of equipotential and may receive little or no shocking effect. If, as with the use of the three electrode system, an electrode of one polarity lies down stream from one of opposite polarity, the relative positions are such as to orient the lines of current flow more nearly parallel to the stream flow and the longitudinal axis of the fish (Figure 10). Such a relationship places a fish's longitudinal axis across the lines of equipotential and greatly increases its chances of subjection to a maximum difference in potential.

We have constructed a slightly different electrode system for use in ponds, small lakes, and deep stream holes. This unit is formed of two large, semicircular, loops of 3/4 inch copper tubing attached to 15 foot red-wood handles (Figure 11). These electrodes are designed primarily for boat operations but may be



used in stream holes by handlers wading the shallows and probing the depths. Each of these probes is equipped with a pendant switch which permits the handler to control the current so as to be able to position the electrode in the water prior to the introduction of the electricity. As with the stream unit, one probe may be positive and the other negative, or by use of an intermediate negative, both probes may be positive. With this system, attached to a 230 volt direct current generator, it is possible to "lead" the fish sufficiently close to the boat to allow easy capture with a dip net. The effectiveness of this unit under various conditions has not been fully explored, but two successful sampling trials have been carried out on one lake. During the second trial, using two positive probes, we discovered that the fishing success was considerably higher at night. This may possibly be attributed to the influence of the underwater light used during night operations. In any case, the fish were much more readily brought into the electrical field.

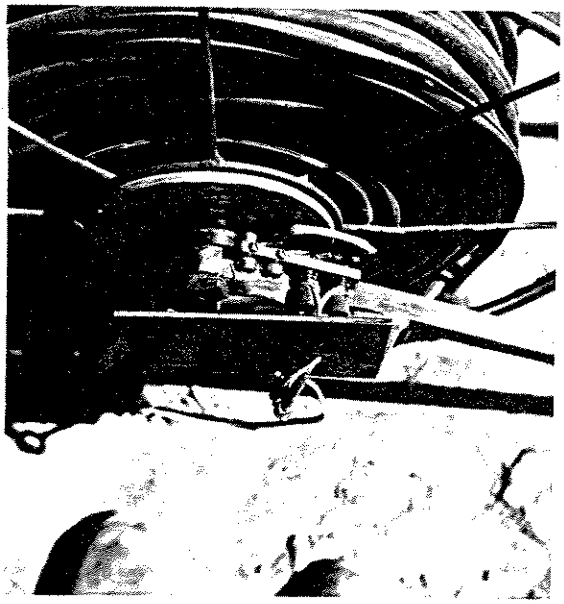
Miscellaneous equipment

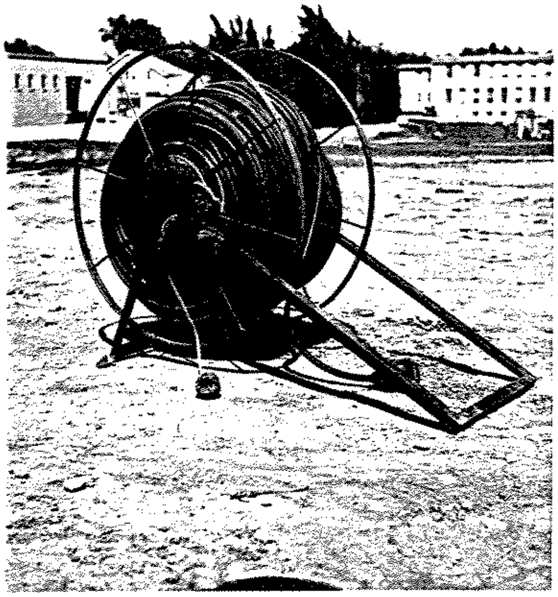
During the electrofishing operations of these investigations we have had occasion to develop several miscellaneous techniques which we have found to be useful.

Any sizeable stream shocking operation requires the use of a great length of cable to connect electrodes

2
20

and generator, if the latter is not to be frequently moved. No matter how carefully coiled, the cable usually becomes snarled and snagged and necessitates constant untangling. It was felt that winding the cable on an ordinary reel would help considerably to reduce the snarling which frequently occurs. We found that a 150 foot capacity garden hose reel will accommodate about 500 feet of #16 cable. With this type of reel the cable is easily transported to the site of operations, is ready for use with a minimum of preliminary straightening, and is easily rewound. A further improvement was made by the addition of a simple sliding contact, designed by Mr. John Dean of the Colorado A and M Electrical Engineering department, which permits the cable to be stripped from the reel, as needed, without detaching from the generator. The contact (Figure 12) consists of a pair of carbon brushes attached to the reel stand. The brushes, which can be connected to the generator, make contact with a pair of brass rings, embedded in an insulating disc centered on the axle and fastened to the side of the reel. The leads of the cable are tapped into the back surfaces of the brass rings, and this junction is adequately protected by the reel drum. A steel guard, welded to the stand, prevents damage to the brushes and their holders, as well as the outer surfaces of the brass rings. The entire stand is reinforced with steel angle-iron





(Figure 13). One man can easily lift the loaded reel from the back of a pickup truck, and wheel it wherever needed. The reel and sliding contact are little the worse for wear after many shocking operations and have proven to be temper and time savers.

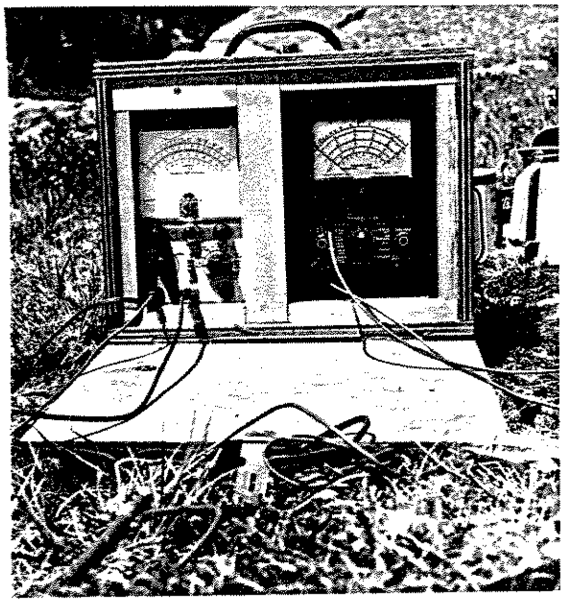
Recent operations have been facilitated by one other modification properly mentioned in conjunction with the reel. Our cable is divided into 100-foot lengths. This permits the removal of sections of varying length from the reel unit, but also necessitates a series of connections which must be able to resist considerable strain without separating. For this we have found the two-wire, 250-volt, 20-ampere armored Twistlock connections to be very satisfactory. The two halves of the connections are covered with rubber sheaths which, while not watertight, protect them against rock damage and streamline them against snagging.

Use of Boats to Float Generators

We have found that many stream areas and ponds are much more easily worked when the power plant can be towed shortly behind the electrodes. For this purpose, we constructed a small, flat-bottomed, boat based on the design described by Myers (1951). Trials with this craft proved it to be satisfactory, but to be lacking in the all-around convenience of a two-man rubber life raft. In using the latter, the generator carrying frame can be placed across the boat without endangering its stability, and the buoyancy of the craft is such as to allow it to be partially filled with water and serve simultaneously as an insulated floating live car (Figure 14). A life raft of this type will not only float the generator and a considerable quantity of water, but also one or two men. For this reason the raft can often provide emergency transportation across deep holes or, with a little upstream maneuvering, bring a net-man out over an otherwise inaccessible deep area. These rafts are of very shallow draft and can be pulled through most riffle areas. They are amazingly resistant to wear, and occasional pontoon leaks are easily repaired with hot or cold tire patching equipment. Finally, from the standpoint of the fishery field worker, in whose truck space is often at a premium, the small storage space required is an important consideration.

Testing Equipment and Its Use

Both McMillan (1928) and Haskell (1954) have shown that the head-to-tail alternating current voltage necessary to produce paralysis in fish is constant regardless of fish size. McMillan, working on chinook salmon, calculated this voltage to be about 3.7 volts, while Haskell, for hatchery and wild brown trout, has given a value of 3.1 volts. From the standpoint of field



23 work the two values may be considered identical. It follows of course that, if the head-to-tail voltages required for paralysis are the same for fish of various sizes, then the paralyzing voltage gradient, or volts per inch, across a large fish will be lower than across a small fish, and a voltage gradient in the water sufficient to paralyze a small fish will be more than sufficient for larger ones. Both McMillan and Haskell have shown that the effective voltage gradient in water depends on the water resistivity and that, in water of high resistivity, the water voltage gradient necessary for paralysis is greater than in water of low resistivity. In water with a specific resistance of 35,000 ohms per cubic centimeter, Haskell has shown that a water gradient of 1.6 volts per inch will impress one volt per inch, across a 3.5 inch fish. This would produce a head-to-tail voltage of 3.5 and paralysis. In a series of field tests we have been able to obtain complete paralysis on 4.5 to 13.0 inch brown trout subjected to gradients of between 0.6 and 1.0 volts per inch in water of 17,000 ohms per cubic centimeter of specific resistance. On the basis of these data we have assumed for field work, that a water voltage gradient of 1.6 volts per inch will be sufficient to produce paralysis on all fish over three inches long, in most waters. Much of our testing and comparison of equipment has been relative to electrode sizes and spans and

generator outputs necessary to maintain this gradient midway between electrodes in various types of water. For these determinations we have used a voltage gradient probe based, in design, on the description of Applegate, et al, (1952) and personal correspondence with the Cook Research Laboratories of Chicago, and made to measure the voltage across one inch of water. This probe is attached to a vacuum-tube voltmeter which, drawing almost no power from the circuit being investigated, provides maximum measuring accuracy. By moving the probe in the field between our electrodes we have been able to determine all the variations which exist in such a field for any given set of conditions. The source of power for the voltmeter has been a 110 volt alternating current portable generator carefully controlled by a field rheostat.

In addition to the vacuum-tube voltmeter we have had the use of a battery operated volt-ohmmeter, which, while lacking sufficient accuracy for voltage gradient tests, has proved to be invaluable for general resistance readings, checking circuit continuity and voltage output, and locating circuit breaks. Both these meters are relatively delicate instruments, but we have found that, enclosed in a substantial wooden case lined with sponge rubber, (Figure 15) they have sustained no damage even though transported with a quantity of additional equipment in the rear of a pickup truck.

Chapter III

WATER RESISTIVITY AS RELATED TO ELECTROFISHING

Many factors affect the efficiency of any electrofishing unit. Water flow and volume, stream bottom conditions, surface area of electrodes, and size of generator, may all be limiting elements. Much investigation of these relationships yet remains to be accomplished. In the Rocky Mountain region, an additional factor, the electrical resistivity of water, seems to warrant a more extensive examination than has been considered necessary by workers in the Eastern states. It is for this purpose that we present the following data from numerous investigations.

Several years ago on a stream in southwestern Wyoming some interesting observations were made on the limitations imposed on electrofishing operations by water conductivity. The electrofishing apparatus used consisted of the standard paddle-type electrodes and 110-volt, 500-watt alternating current generator with an attached voltmeter and an ammeter. An initial shocking operation in the stream's mountain headwater area met with no fishing success. Possibly no fish were present, but the relative values shown on the meters indicated a more probable answer. The voltmeter showed the output to be well over the rated 110 volts while the ammeter showed almost no current. Unquestionably the water in this stream area was so lacking in dissolved solids as to be almost incapable of electrical conductivity. At this time we little understood the implications of these measurements and gave little further attention to the matter. Subsequently, operations were shifted to a meandering, lowland section on the same stream. Again we achieved little fishing success, but this time the meters showed a reversal of their relative values and we obtained an off-scale ammeter reading with an exceedingly low voltage reading. The dissolved solids in this stream section were probably so plentiful as to produce maximum current conductivity at a voltage too low to produce a voltage gradient sufficient to shock fish.

Repetition of these experiences points to the necessity of a more complete understanding of the electrical resistivity of water and its relationship to dissolved solids and water temperatures. That comparatively little information is present in the electrofishing literature, is probably explained by the fact that, in those areas where much electrofishing development has taken place, the extremes of water resistivity are largely within a range concordant with standard equipment. McMillan (1928) in working out requisite voltage gradients for satisfactory operation of electrical fish barriers points out the great importance of water resistivity. He goes on to develop a method for calculating the voltage gradient required to shock fish in waters ranging in specific resistance from 10 to 10,000 ohms per cubic inch. Values in ohms per cubic inch may be converted to ohms per cubic centimeter by multiplying by a conversion factor of 2.54. The listed upper limit of resistivities, however, is considerably lower than what may be encountered in some of Colorado's waters. Haskell (1954) also points out the importance of water resistivity and its relation to water temperature, but here again the listed limits of 1500 and 35,000 ohms per cubic centimeter are greatly exceeded in certain Colorado waters. Much of the development of practical electrofishing equipment has been accomplished in Germany and in recent correspondence with the Bundesanstalt für Fischerei at Hamburg we have been informed that German electrofishing equipment has been developed for use in waters having specific resistances between 1000 and 15,000 ohms per cubic centimeter. Our investigations of Colorado waters for this electrofishing project have shown that specific resistance limits may extend from less than 200 to greater than 40,000 ohms per cubic centimeter.

Much of Colorado's stream water originates in non-soluble granitic areas and flows for considerable distances over substrates of the same material. In these waters the total dissolved solids present are low and the specific resistance relatively high. On the other extreme Clarke (1924) shows that many prairie streams, which have passed through extensive areas of irrigated arid soil, have picked up great quantities of soluble saline material which together with excessively warm summer temperatures often reduce water resistivity to such an extent that standard electrofishing equipment is impractical. The streams and reservoirs of eastern Colorado represent this extreme. For any given set of electrodes and generating unit there is, what might be termed, an optimum range of effectiveness. Due to the peculiar and varying nature of an electrical field in a stream situation, this optimum range appears to be difficult to ascertain exactly. A knowledge of the approximate resistivity between a given set of electrodes at a constant span, related to the generator's rated ampere capacity and an effective electrofishing voltage gradient, will provide a good indication of the limit for waters of low resistance. For example, in the Arkansas River at Granada, an electrode span of six feet had a resistance of 10 ohms. If our 230 volt direct current generator were able to maintain a 230 volt output the current would be 23 amperes which would constitute a sizeable overload above the 10.9 ampere rating. In actuality, however, while there may be sufficient overloading to cause heating, the principal reduction in shocking effectiveness results from a marked drop in the difference in potential along the circuit. In other words the voltage necessary to overload the circuit remains well below the rated output and consequently reduces to ineffectiveness the voltage gradient possible with the six foot span in question. Sufficient reduction of the span will increase the voltage gradient to an effective strength, but soon decreases the effective range of operation to impracticability.

In many of our head water areas the problem is quite different. Here the resistance of the water may be so great that there is no chance of a current overload, but the maximum output of a 110-volt machine is incapable of producing a satisfactory voltage gradient, and even a machine producing 230 volts or greater will permit only a limited electrode span. Actually an increase in the electrode span appears to decrease the resistance between the electrodes due to the great increase in diameter of the conducting medium. At least we have found indications of such an increase in current carrying capacities. In this situation the voltage gradient decrease which occurs with such an extension of the electrode span may be due to increased conductivity and/or dispersion of the electrical current flow throughout a much greater volume of water.

From these considerations it becomes obvious that for a particular electrode system and a generator of given voltage and amperage capacity there will be both a minimum and a maximum water resistance at which we can expect effective electrofishing. With our direct current unit, which produces 10.9 amperes at 230 volts, any decrease in total circuit resistance below 21.5 ohms will produce a simultaneous reduction below an effective voltage gradient. Observations at the other end of the scale seem to indicate that resistances greater than 600 ohms also adversely affect the voltage gradient. With our alternating current unit, rated for 2.17 amperes at 230 volts, the minimum total circuit resistance, not allowing for inductance, appears to be approximately 100 ohms. This unit, however, has proven effective in waters of sufficiently high resistance to make the direct current machine virtually useless. Unquestionably this is in part due to physiological reactions produced by cyclic current, but it should be also pointed out that the 230 volt designation for alternating current refers to what is known as the effective voltage, and that the peak voltage of 325 volts may play an important part in producing the greater effectiveness of alternating current in waters of high resistance.

Upon considering these relationships of electrical resistance of water to the effectiveness of electrofishing apparatus it seemed that it might be useful to have some method for a rough prediction of shocking success. Electrofishing is a technique often used for sampling fish populations both as to quantity and quality. In this respect it has been our experience that lack of fishing success may lead to the conclusion that fish are not present, whereas in reality, the answer may lie in equipment failure produced by the aforementioned water conditions. Any testing technique which will point to the presence of these conditions will assist in a more accurate reporting of electrofishing success and may also serve to forestall the expenditure of unnecessary time and effort on nearly unshockable waters. A relatively accurate prediction is possible with a vacuum tube volt-ohmmeter, but involves a lengthy testing procedure as well as the transportation of considerable fragile equipment with which few field men will care to be burdened. To be at all practical such a test should be simple and involve as little additional equipment as possible. As already mentioned, some indication of water resistivity may be obtained from a rough analysis of volt meter and ammeter readings. With experience one should be able to recognize a volt-ampere relationship at which electrofishing seems to be optimum.

The data provided by the standard methyl orange test for total alkalinity (Ellis, _et al_, 1948), expressed in parts per million of calcium carbonates, appeared

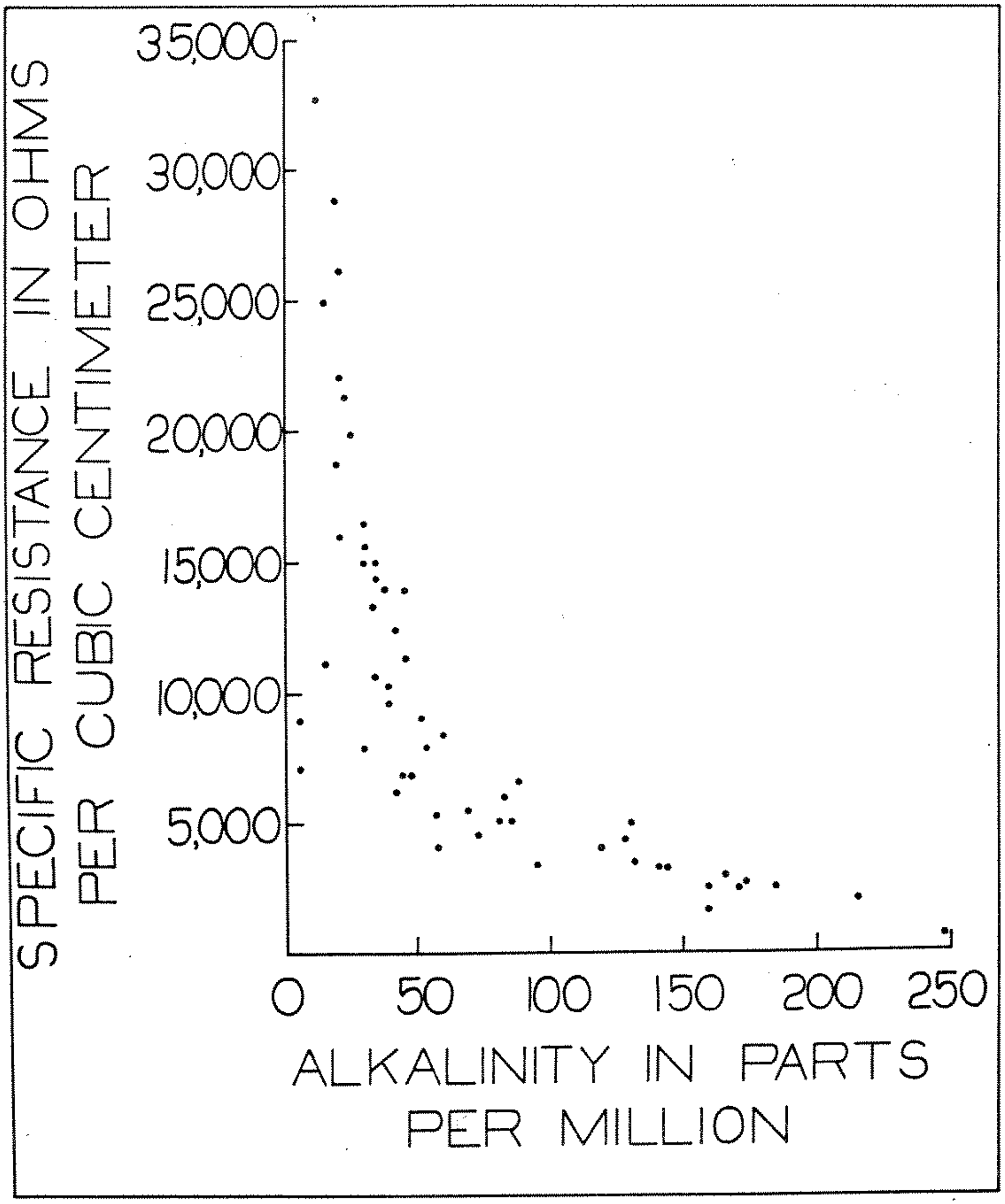

SPECIFIC RESISTANCE IN OHMS PER CUBIC CENTIMETER
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
50
100
150
200
250
ALKALINITY IN PARTS PER MILLION

Table 2.--METHYL ORANGE TOTAL ALKALINITY AND SPECIFIC RESISTANCE READINGS TAKEN DURING OCTOBER, 1954.

Stream Name	Sample Location R	T	S	Specific Resistance at 70° F. Ohms/cc*	Total Alkalinity ppm**
Laramie River	75W	8N	19	11,250	46
Two One-half Cr.	75W	8N	19	16,500	29
Cache la Poudre	75W	7N	5	22,300	20
Cache la Poudre	75W	8N	21	25,200	17
Cache la Poudre	70W	8N	14	13,600	35
Cache la Poudre	70W	8N	24	8,160	53
Big Creek	81W	12N	30	15,000	30
N. Fk. N. Platte	82W	11N	26	12,800	42
Forest Creek	82W	11N		25,800	18
North Platte	80W	10N	2	2,400	161
Big Dry Creek	68W	1S	22	640	248
Bear Creek	70W	5S	2	10,700	35
Deer Creek	72W	7S	15	18,900	19
N. Fk. S. Platte	72W	7S	29	11,100	16
N. Fk. S. Platte	75W	7S	12	9,100	5
Jefferson Creek	75W	8S	5	15,700	32
Tarryall Creek	76W	8S	27	6,000	84
South Platte	77W	9S	33	5,200	86
S. Fk. S. Platte	77W	11S	23	2,600	173
Trout Creek	77W	13S	3	3,500	132
Arkansas River	78W	14S	22	7,400	47
Chalk River	78W	15S	14	7,400	49
S. Arkansas River	8E	49N	10	3,300	143
San Luis Cr. Trib.	8E	48N	22	4,300	128
Saguache Creek	7E	44N	13	6,700	79
Russel Lake Inlet	7E	43N	24	5,200	82
Rio Grande, S. Fk.	3E	40N	34	14,200	46
Rio Grande, N. Fk.	3E	40N	33	14,100	38
Clear Creek Trib.	3W	41N	1	15,000	34
Corral Creek	3W	42N	2	21,400	22
Cibolla Creek Trib.	3W	43N	35	29,100	18
Trib. Lake San Cristobal	4W	43N	13	7,200	5
Lake Fork of Gunnison	4W	43N	10	8,100	31
Lake Fork of Gunnison	4W	48N	3	6,600	44
Sapinero Creek	4W	49N	28	5,600	69
Gunnison River	4W	49N	27	4,200	118
Tomichi Creek	1E	49N	12	3,300	142
Anthracite Creek	87W	14S	4	16,000	21
N. Fk. Gunnison R.	89W	13S	8	10,200	40

Table 2.--METHYL ORANGE TOTAL ALKALINITY AND SPECIFIC RESISTANCE READINGS TAKEN DURING OCTOBER, 1954 (Continued).

Stream Name	Sample Location			Specific Resistance at 70° F. Ohms/cc*	Total Alkalinity ppm**
	R	T	S		
Muddy Creek	89W	12S	33	5,000	130
Crystal River	88W	10S	17	4,100	57
Frying Pan River	86W	8S	8	5,400	58
Roaring Fork	87W	8S	12	3,400	97
Colorado River	87W	5S	30	3,000	165
Deep Creek	86W	4S	30	1,700	160
Derby Creek	85W	2S	22	2,000	215
Rock Creek	83W	2S	6	2,500	170
Colorado River	82W	2S	18	4,700	75
SheepHorn Creek	82W	1S	35	2,500	183
Blue River	80W	1N	20	5,200	82
Colorado River	76W	2N	21	14,600	36
Willow Creek	77W	3N	34	9,100	52
Illinois River	78W	6N	30	8,700	60
Michigan River	76W	6N	10	9,700	39
Joe Wright Cr.	75W	7N	18	19,800	23
Trap Creek	75W	7N	7	33,000	12

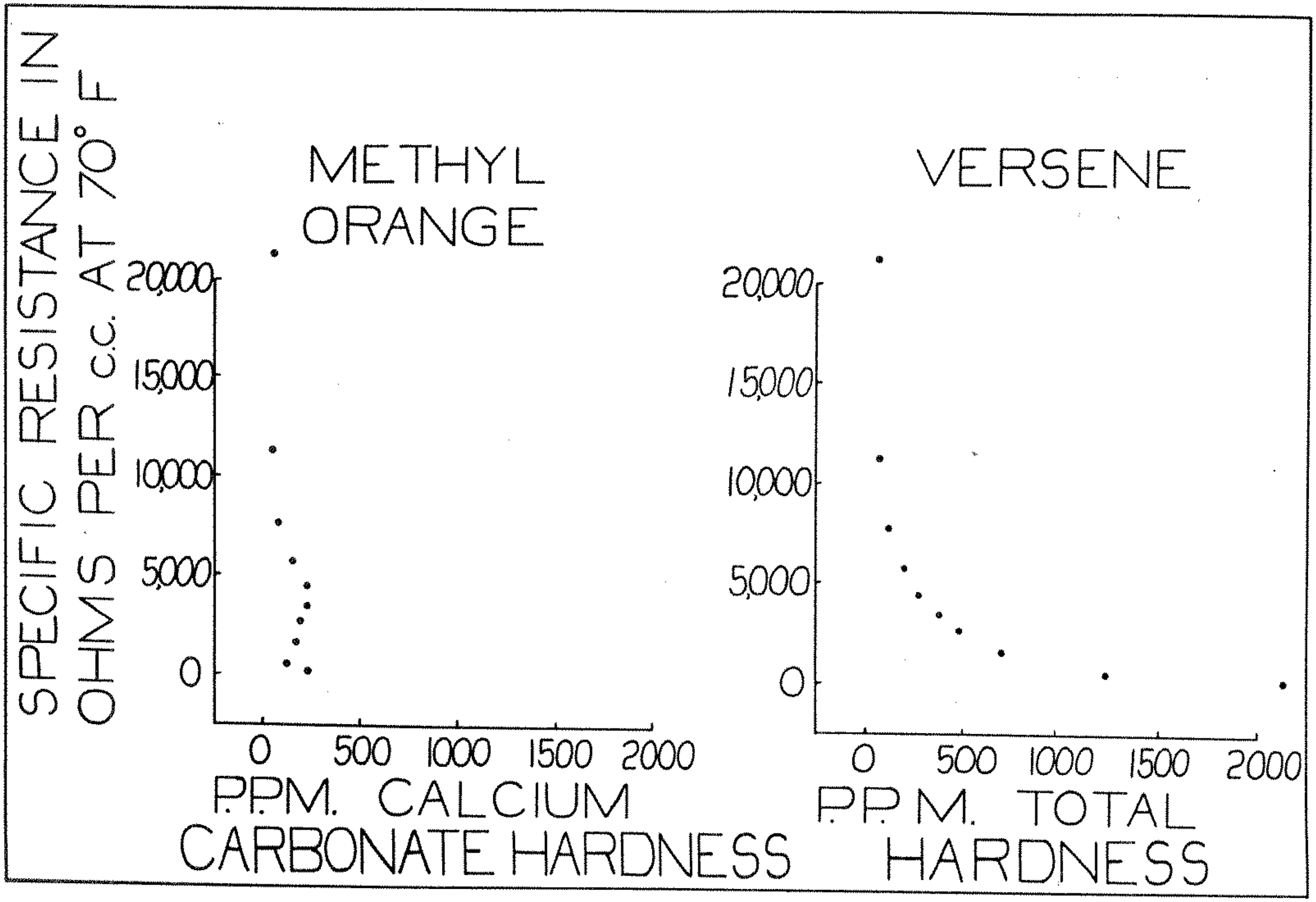
* cubic centimeter
** parts per million

initially to correspond closely to specific resistance readings made with a conductivity bridge and cell. A total of 56 samples, taken from the North Platte, South Platte, Arkansas, Rio Grande, Gunnison and Colorado River drainages, indicated a definite correlation between the two tests. These data are shown in Figure 16 and Table 2. While this correlation appeared to be generally consistent, there were a few methyl orange readings which failed to account for some comparatively low resistance readings. About this time it was suggested that the Versene total hardness test, which records almost all positive ions, as compared to the carbonate measure of the methyl orange test, might provide us with a more accurate relationship, and so an additional series of 20 samples was taken on which Versene hardness, methyl orange alkalinity, and specific resistance tests were made. The data for ten of these samples which appear to be representative of the lake and stream waters of Colorado are presented in Table 3. In Figures 17 and 18 the dispersion of the methyl orange and Versene readings may be compared, relative to identical specific resistance values. From these graphs it may be seen that, while specific resistance and Versene values retain a comparatively consistent relationship, there is a rather confused scattering of methyl orange values relative to the waters in the lower specific resistance ranges.

Table 3.--WATER RESISTIVITY AND HARDNESS DATA FOR TEN COLORADO WATERS.

Name of water	Location R	T	S	Water Temp. °F.	Ohms/cc[a] @ water temp.	Ohms/cc @ 70 °F.	Water MO[b]	Hardness Versene
Big South Fork Cache la Poudre River	78W	8N	28	34	34,500	21,200	22	17
North Fork South Platte River	72W	7S	29	41	17,300	11,600	22	34
Lake Fork Gunnison River	4W	43N	15	37	11,900	7,500	42	68
Brush Creek	5E	48N	16	35	9,100	5,600	80	86
North Fork Cache la Poudre River	70W	9N	33	46	4,200	3,100	170	170
State Fish Hatchery Bellvue, Colo.	70W	8N	35	58	2,600	2,200	165	239
Cimarron Creek	6W	48N	8	45	1,900	1,300	132	291
Reservoir No. 4	68W	9N	29	48	920	690	125	600
Blue Lake	48W	22S	2	54	280	230	105	1,265
Nee Gronda Res.	48W	20S	14	47	220	160	150	2,086

a Ohms per cubic centimeter
b Methyl Orange


SPECIFIC RESISTANCE IN
OHMS PER c.c. AT 70° F
METHYL
ORANGE
20,000
15,000
10,000
5,000
0
0
500
1000
1500
2000
P.P.M. CALCIUM
CARBONATE HARDNESS
VERSENE
20,000
15,000
10,000
5,000
0
0
500
1000
1500
2000
P.P.M. TOTAL
HARDNESS

9

Besides a more complete measurement of the dissolved solids in water the Versene method offers three additional advantages. Firstly, the entire unit weighs about ten ounces and is contained in a 4 1/2 x 4 x 1 3/8 inch plastic case. Secondly, like the methyl orange test, Versene employs a titration, but it is comparatively rapid and requires only a small pipette. Thirdly, the color change denoting the end point of the titration is more pronounced than that encountered in the methyl orange test.

It should be emphasized that the use of the Versene test, relative to water resistivity, represents only a practical general indicator not an exact measure. The Versene test, as here described, measures total hardness in parts per million by drops, each drop representing 17.1 ppm of hardness. Experience will enable the investigator to tell quite accurately when he is approaching the end-point, and upon which end of the 17.1 ppm range it occurs. Certainly for the purpose proposed, the accuracy is sufficiently satisfactory.

As may be seen in Table 3, the specific resistance of water may change considerably with water temperature. Neither Versene nor methyl orange tests register this variation. If the specific resistance of a stream is known for any given temperature, then the approximate specific resistance may be calculated for any other temperature by use of a temperature factor table (Table 4). It is probable that Versene readings for waters of known specific resistance may be used to form rough estimates of the specific resistances of similar temperatures in untested waters. For example: the Versene hardness of a stream is found to be 86 ppm; in Table 3, 86 ppm corresponds with a specific resistance of about 5600 ohms per cubic centimeter at 70° F.; by means of Table 4 it is possible to calculate the approximate specific resistance for 77° F., which in this case would be about 5100 ohms per cubic centimeter; if the actual stream temperature were 40° F. then the specific resistance at that temperature is roughly 8400 ohms per cubic centimeter, and this value may be related to an electrode resistance for waters of similar specific resistance. Specific resistance values for our paddle electrodes at a span of six feet have been found to average about 28 times the resistance measured in ohms per cubic centimeters. This relationship would hold only for this particular unit, but a similar one can be established for any electrofishing unit. It remains to be determined with what degree of consistency these calculations will apply to a variety of waters.

Table 4.--TEMPERATURE FACTORS, f_t, FOR USE IN CORRECTING RESISTANCE TO THE STANDARD TEMPERATURE OF 77° F. USING THE EQUATION: $R_{77} = R_t/f_t$**

°F.	f_t	°F.	f_t	°F.	f_t
37.4	1.727	71.6	1.067	84.2	0.923
39.2	1.678	72.0	1.062	84.6	0.920
41.0	1.631	72.3	1.058	84.9	0.917
42.8	1.585	72.7	1.053	85.3	0.914
44.6	1.541	73.0	1.048	85.6	0.909
46.4	1.499	73.4	1.044	86.0	0.906
48.2	1.460	73.8	1.039	86.4	0.903
50.0	1.421	74.1	1.035	86.7	0.899
51.8	1.384	74.5	1.030	87.1	0.896
53.6	1.350	74.8	1.026	87.4	0.892
55.4	1.316	75.2	1.021	87.8	0.888
57.2	1.284	75.6	1.017	88.2	0.885
59.0	1.254	75.9	1.013	88.5	0.882
60.8	1.224	76.3	1.008	88.9	0.879
62.6	1.196	76.6	1.004	89.2	0.876
64.4	1.168	77.0	1.000	89.6	0.873
64.8	1.163	77.4	0.996	90.0	0.870
65.1	1.158	77.7	0.992	90.3	0.867
65.5	1.152	78.1	0.987	90.7	0.864
65.8	1.147	78.5	0.983	91.0	0.861
66.2	1.142	78.8	0.979	91.4	0.858
66.6	1.137	79.2	0.975	93.2	0.843
66.9	1.132	79.5	0.971	95.0	0.828
67.3	1.128	79.9	0.968	96.8	0.814
67.6	1.123	80.2	0.964	98.6	0.801
68.0	1.118	80.6	0.960	100.2	0.787
68.4	1.113	81.0	0.956	102.2	0.774
68.7	1.108	81.3	0.952	104.0	0.761
69.1	1.102	81.7	0.949	105.8	0.749
69.4	1.097	82.0	0.945	107.6	0.738

Table 4.--TEMPERATURE FACTORS, f_t, FOR USE IN CORRECTING RESISTANCE TO THE STANDARD TEMPERATURE OF 77° F. USING THE EQUATION: $R_{77} = R_t/f_t$[*][**] (Continued).

°F.	f_t	°F.	f_t	°F.	f_t
69.8	1.092	82.4	0.941	109.4	0.727
70.2	1.087	82.8	0.937	111.2	0.716
70.5	1.082	83.1	0.934	113.0	0.706
70.9	1.077	83.5	0.930	114.8	0.695
71.2	1.072	83.8	0.927	116.6	0.685

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[*] Adapted from L. A. Richards, The Diagnosis and Improvement of Saline and Alkali Soils U. S. Department of Agriculture Regional Salinity Laboratory, 1947.

[**] R_{77} = Specific Resistance at 77° F. R_t = Specific Resistance at known temperature; f_t = correction factor.

Unfavorable shocking conditions related to temperature and water conductivity may be partially offset by increasing the operating rate of the generating unit. Such an increase results in an increase in the output voltage. Increasing the output voltage produces a proportional increase in the water voltage gradient for a constant electrode span. As an example in 1000 feet of a mountain stream, with a specific resistance of 40,000 - 45,000 ohms per cubic centimeter, we found it impossible to shock with 225 volts of either alternating or direct currents. At this voltage the voltage gradient for a seven foot span of our electrodes was 1.0 volt per inch which was inadequate for efficient operation. By increasing the revolutions per minute of our alternating current machine we were able to obtain an output of 360 volts and a voltage gradient of 1.6 volts per inch for the same electrode span. Shocking the same 1000 feet with this voltage increase we had no difficulty in taking 36 trout ranging from two to twelve inches in length. A similar comparison on a lower section of the same stream produced almost identical results. While the generating equipment may tolerate revolutions per minute increases for limited periods, such a practice is not to be recommended, as it will shorten the life of the machine. In addition to voltage increase there are some other considerations which may assist in an improvement of electrofishing effectiveness in high resistance waters. In general we have observed that such waters may be more effectively worked in the late summer or early fall. During this period the water volume is usually at its lowest point, and fish, which are shocked, will not be rapidly carried away. Furthermore, low water conditions will often confine the fish to small areas of deep water, making it possible to subject them to a more concentrated electrical field. An additional advantage, at this time of year, results from an increase in water conductivity due to increased concentrations of dissolved solids and higher water temperatures.

In waters of extremely low resistivity the problem of increasing shocking effectiveness appears to be less easily solved. The obvious answer is to use equipment of a sufficient capacity to carry heavy current loads. According to the U. S. Fish and Wildlife Service's recent review of European electrofishing developments, (Houston, 1949) Germany has had considerable success with electrofishing techniques in salt water. It is pointed out, however, that the high conductivity of sea water necessitates the use of extremely high powered electrical equipment. Peterson (1952) described one of the German saltwater units as a 400,000 watt direct current generator capable of producing pulsed current with peaks as high as 25,000 amperes. The equipment required for successful electrofishing in some of Colorado's saline waters would probably not approach such high capacities, but it would have to be of a higher current carrying capacity than that of the standard portable machines. As has been previously stated, the use of a generator with a low current capacity in waters of high conductivity drops the voltage gradient below a practical level. We have encountered this situation with our direct current machine which has a 10.9 ampere current rating. Our alternating current machine has a 2.17 ampere rating which is comparable to that of many of the portable machines commonly used for electrofishing and is almost entirely ineffective in saline waters.

It appears possible that some use might well be made of the seasonal relationship to water temperature and dissolved solids concentration proposed for highly resistant waters. Many waters are probably so highly conductive as to be insufficiently affected by these factors, but further investigation might show that some could be shocked during the spring of the year when a combination of run-off dilution of dissolved solids and low water temperatures would raise electrical resistance to a practical level.

Chapter IV

SOME OF THE PHYSIOLOGICAL EFFECTS ON FISH SUBJECTED TO ELECTRIC CURRENT

An extensive search of electrofishing literature shows very little reference to specific examples of injury or mortality among fish shocked during electrofishing operations. The investigations of McMillan (1928) relative to electric fish screens showed that fish subjected to an alternating current field suffered a marked increase in mortality for increased exposure times over those necessary for immobilization, but little attempt at physiological evaluation was made. In a 1933 review of Russian electrofishing problems, Delov and Tomashevskii (1933) mention the frequent occurrence of mortality in connection with the use of alternating current. Smolian (1944) in his general review of German electrofishing, has mentioned that high voltages sometimes produce injuries which may include external markings, intra muscular hemorrhages, and rib fractures. He has further pointed out that, among species, there appears to be a fairly close negative correlation between sensitivity to anoxemia and the ability to recover from the effects of electric shock.

In an effort to compare the lethal effects of direct and alternating currents, we ran a series of electrofishing tests in which the situation would simulate stream conditions, but also allow close observation of the fish over a period of time. These tests were carried on at the Colorado State Fish Hatchery at Bellvue. Here a graveled-bottom cement raceway 35 feet long and 6 feet wide was made available. The fish used were eight to twelve inch rainbow trout obtained from the Colorado State Trout Rearing Station at Drake. After transportation from the rearing station they were allowed an overnight acclimatization period and, on the day of shocking, appeared to be in excellent condition.

For this entire series of tests, we used our standard electrofishing apparatus. The two electrodes were the paddle-type elsewhere described. Alternating current was supplied by a 230 volt, 500 watt, 60 cycle, Onan Electric Plant, and was controlled by a variable transformer. The direct current machine was a 230 volt, 2500 watt, Homelite, to which was attached a field rheostat for current control. The voltage checks were made with a Simpson Volt-Ohmmeter.

Prior to shocking, all the fish were removed from the raceway and placed in live boxes in the next upstream raceway, outside the range of the electrical field. As the lower end of the raceway was blocked by a metal screen and the upper end by wooden baffles, it was decided to shock in an upstream direction so that any fish trapped at the end of the run would not be subjected to shielding by the metal screen. For the sake of accuracy, each shocking run was made in a manner as similar to a standard pattern as possible. Starting at the lower end of the raceway one of the two operators handled the electrodes and the second, a dip net and a small floating live car which he towed about seven feet behind the electrodes. The same man handled the same job throughout the series of tests. With the electrodes separated by the six foot width of the raceway, the electrode operator moved steadily along the entire length of the raceway, while the net man followed and recovered the shocked fish as rapidly as possible and placed them in the floating live car. Prior to the actual application of electric current, all the fish for each test were herded away from the lower end of the raceway so as to prevent accidental trapping down stream from the electrodes.

Twenty fish were subjected to each of three different electrical conditions, and an additional thirteen fish were held as controls but were handled exactly as the others except for shocking. The first group of fish was shocked with 220 volts of alternating current. The second group was shocked with 160 volts of alternating current for which condition the peak voltage was calculated to be about 220 volts. This group of tests was made because we felt that an examination of the effects of alternating current having 220 peak volts was necessary for a valid comparison. Most comparisons of alternating and direct current equipment, apparently fail to consider the fact that the voltage conditions produced by machines of equal rating are not actually similar. A 220 volt alternating current generator is actually producing a peak of about 311 volts. While this peak may not represent an effective value from the electrical standpoint, it should be of considerable importance from the physiological standpoint, and is probably a factor in electrofishing effectiveness. The third group was shocked with 220 volts of direct current. As direct current is non-cyclic, there are no peak voltages produced by a direct current generator, and an output measured at 220 volts represents exactly that. All voltages were carefully checked with a volt meter.

The twenty fish shocked with each type of electrical current were first divided into four replications of five fish each. This division reduced the possibility of erroneous deductions being made from a single test. The five fish in each replication were measured, marked for identification, and placed in the raceway. After a three minute interval in which to observe any undue handling effects, we commenced shocking. After shocking, each group was placed in one of the live boxes in the upper raceway. This procedure was followed until the shocking of 60 fish had been accomplished, at which time all the fish were returned to the raceway for observation.

According to the final mortality figures (Table 5) there appears to be an indication of a higher lethality for both ratings of alternating current as compared to direct current. However, statistical comparison of the final mortalities of shocked fish by calculation of the standard error of porportions shows no significant difference among them. Comparing the 55 percent mortality of 220 volt alternating current and the 30 percent mortality of 220 volt direct current we find that there is a 11.0 percent probability of a chance difference due to sampling. Comparison of the proportions of 220 volt alternating current and 160 volt alternating current to the unshocked controls shows that there is respectively a 0.5 percent and a 3.6 percent probability of a chance difference due to sampling indicating that there is a probability of a significant difference between the mortalities of the alternating current shocked fish and the controls. The 13.4 percent probability of a chance difference due to sampling between 220 volt direct current and unshocked controls indicates that there is not a significant difference between the mortalities of these groups. In further comparing the alternating current groups to the direct current it should be noted that in both 220 volt alternating current and 160 volt alternating current the mortal-

Table 5.—A COMPARISON OF MORTALITIES OF 8 TO 12 INCH RAINBOW TROUT SHOCKED WITH 220 VOLT ALTERNATING CURRENT, 160 VOLT ALTERNATING CURRENT AND 220 VOLT DIRECT CURRENT.

	Group I 220 Volts AC				Group II 160 Volts AC				Group III 220 Volts DC				Group IV Controls
Test sub-group	A	B	C	D	A	B	C	D	A	B	C	D	
No. of fish	5	5	5	5	5	5	5	5	5	5	5	5	13
Maximum size	10.6	10.3	10.5	12.3	11.0	10.6	10.3	10.1	10.8	9.9	10.4	11.7	10.5
Minimum size	8.5	8.2	8.9	9.7	8.7	9.0	9.5	8.7	8.2	9.1	8.9	8.1	8.5
Mean size	9.6	8.8	9.8	10.5	9.8	9.6	10.0	9.3	9.7	9.5	9.6	9.7	9.3
Mortality within 6 hrs.	2	2	1	2	1	1	0	1	0	0	0	0	0
Mortality, 6-24 hrs.	1	1	1	0	0	1	1	2	1	1	3	1	0
Mortality, 24-36 hrs.	0	0	0	1	0	0	1	0	0	0	0	0	1
Total mortality after 7 days	3	3	2	3	1	2	2	3	1	1	3	1	1
Total mortality for each group	-	-	-	11	-	-	-	8	-	-	-	6	1
Percent mortality for each group	-	-	-	55	-	-	-	40	-	-	-	30	7.6

ity occuring within the first six hours after shock, was quite high while none occurred in 220 volt direct current. An examination of these initial mortalities showed that all had the open mouths and distended opercula indicative of suffocation. None of the subsequent mortalities from either alternating or direct current groups had these characteristics. All mortalities were autopsied for possible incidence of vertebral or aortic injury, but none was found and the exact cause of death could not be determined. Following the termination of seven days of observation a similar autopsy was made on the remaining shocked fish. Not one instance of such injury was discovered.

In 1949, Walch (1949), who has had much contact with recent German electrofishing development, reported his initial observation of vertebral injury of a type which we believe to be of frequent occurrence in Rocky Mountain electrofishing operations. Walch's own description of the instance is as follows:

> . . .one day I observed in a pool, where brood trout were kept until maturity, a large trout which had been caught with the mentioned alternating current aggregate. Because it was a very fine animal I remembered clearly the circumstances of its catching. It did not show any conspicuous property shortly after catching. Now it swam around, still comparatively rapidly, but with remarkably awkward movements. The last third of its body, from the dorsal fin backwards, showed a sharply outlined black color. . . I killed the animal and investigated. I found during evisceration of the kidney and freeing of the vertebral column that the vertebral column was broken posterior to the dorsal fin; the nerves were still connected. The

> bones which were attached to this part of the vertebral column were freed and had themselves stuck into the muscles and produced a walnut-sized effusion of blood, which could be seen from the outside as a kind of tumor. The animal, which hardly could have been mechanically damaged during or after catching, lived in that condition for about 8-9 weeks. It can be assumed that cramping by alternating current was so great that this fracture of the vertebral column was the result . . . The central nerves were thus squeezed at the point of fracture so that also those nerves which regulate the pigment cells of the skin could no longer act and could not make the cells contract. As a result of this the pigment cells remained in the relaxed position and produced the black color of the latter third of the body. The described trout was 50cm. long and had a weight of about 1550 grams.

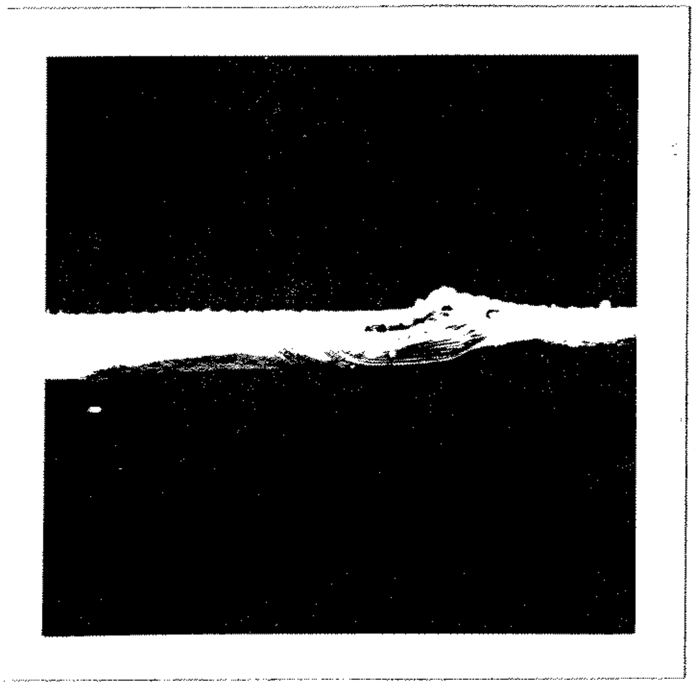
The injury described by Walch almost exactly corresponds to those reported by Hauck (1949) for ten large rainbow trout taken with alternating current. Furthermore, both of these investigators have pointed out that the frequency of external black marks indicate a far greater occurrence of such injury than shown by the few cases autopsied.

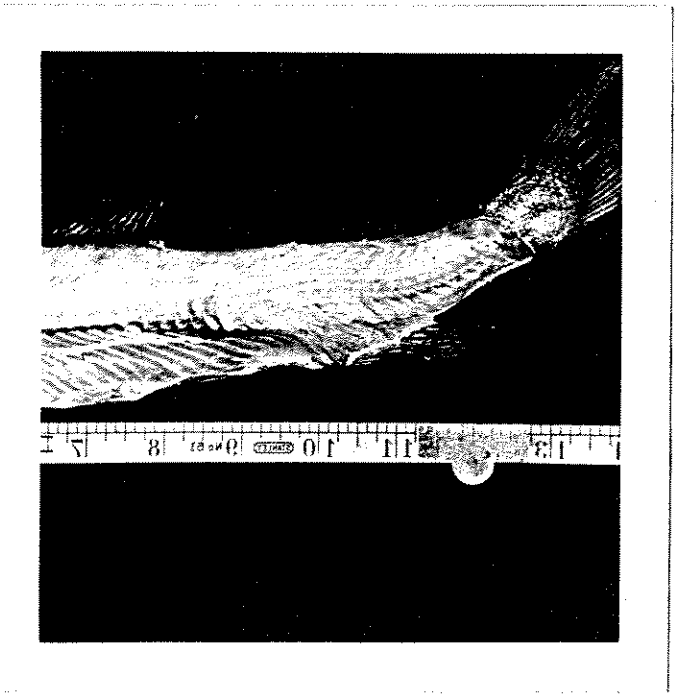
During numerous electrofishing operations, both in Colorado and Wyoming, the injurious and lethal effects of electric current have often been observed. These effects, in general, have appeared in two forms which seem to be related to the size of the fish. Examination of numerous electrocuted fish ranging from two to eight inches in length has shown only three cases of vertebral fracture, whereas in a large number of these fatalities the open mouths and distended opercula indicated probable death by suffocation. On the other hand, examination of larger fish either killed during shocking operations or subsequently autopsied because of the characteristic black markings (Figure 19) has usually disclosed the presence of aortic rupture and/or partial or complete vertebral dislocation or vertebral fracture (Figure 20). In regard to this vertebral injury it should be noted that out of 30 fish autopsied following numerous shocking operations, 29 had sustained the injury between the 20th and 45th vertebrae, and of these, 23 were injured between the 30th and 40th vertebrae. These data, in conjunction with those of Hauck (1949), indicate a preponderance of these injuries occur directly posterior to the dorsal fin or, in other words, that region in which the musculature is most particularly involved in strong or rapid locomotion. At the present time we know of no reference to this type of injury relative to electrofishing with direct current, but, of the above 30 fish examined, five had been taken with 230 volt direct current, and the injury disclosed was in every way similar to those with alternating current.

A review of American electrofishing literature makes it seem as though this type of injury does not occur too frequently in most sections of the country. Haskell, in personal correspondence with this writer, has expressed the belief that alternating current injury

rarely occurs in the eastern states and suggests that the greater frequency in the western states may be related to water quality or size of fish. The latter possibility is, at least in part, substantiated by both our data and those of Hauck (1949). Furthermore, among the larger fish, we believe that the incidence of such injury may often be far higher than generally supposed. In March of 1953, during a spawn-taking operating for the Wyoming Game and Fish Commission, we captured 105 cutthroat trout, Salmo clarkii, with a 110 volt, alternating current shocker. These fish ranged in size from 11 to 22 inches in total length with an average length of 18.5 inches. Of these 105 fish, 32 showed the external markings typical of vertebral injury or aortic hemorrhage. An autopsy of five of these individuals, that died during retention, disclosed either vertebral fracture or dislocation. These five, representing approximately 5 percent of the total number taken, are the known mortality, but, nothing is known as to what percentage of the remaining total may have died following release. A further indication of a possible high incidence of injury was given in August of 1954. While attempting to determine the effectiveness of a 360 volt alternating current output in water of extremely high resistance, we captured 12 cutthroat trout, ranging from 8 to 12 inches in length, and held five which showed external marking for observation. These fish were subsequently autopsied. Of this group, three had suffered vertebral fracture or dislocation, and the remaining two had sustained very marked aortic hemorrhage.

At this point it should be brought out that, while serious vertebral injury may result in death within a short time, there is evidence of greatly delayed mortality as well as some degree of recovery. On November 1, 1951, the field crew responsible for fishery management in western Wyoming shocked and captured for spawning a sizeable number of brown trout, several of which, showing evidence of injury, were placed in a large artificial pond for long-term observation. On May 8, 1953, one of these fish was found dead and an autopsy was made. This particular specimen weighed 539 grams and measured 15.75 inches in length in November, 1951. At the time of death its weight was 229 grams and its length was 15.0 inches. Its general "snaky" appearance and lack of any mesenteric fat indicated a starved condition. Examination of the spinal column revealed a pronounced right lateral enlargement of the 33rd vertebra (Figure 21) indicating healing of a previous fracture; and a fracture of the right branch of the neural arch that had failed to heal. In the vicinity of this injury, the spinal column appeared to be incapable of any right lateral flexure, and its overall appearance and that of the entire body was one of permanent upward flexure of the caudal area (Figure 22), as





well as left lateral flexure of the body both anterior and posterior to the injury. Prior to the death of this fish we had observed that several of this group appeared able to swim only in circles. This condition may have contributed largely to its starvation and eventual death. As a result of the findings made on this fish, we decided to examine four other members of the group, that appeared to have sustained injury at the time of shocking. On one, with left lateral enlargement of the 39th vertebra, the weight had dropped from 397 to 340 grams, the total length had changed from 14 to 13.75 inches, and a general appearance of starvation was evident. In the additional three specimens examined there were no unusual changes in weight or length and general body condition appeared to be normal. Examination of the spinal columns of all three, however, revealed pronounced lateral enlargement of posterior abdominal or caudal vertebrae and some degree of deformation, indicating the probability of a healed fracture. Two of these fish were over 14 inches in length and the third was 12.5 inches.

The problem now arises as to what are the physiological effects producing these injuries and mortalities. Because of the great difference between the physiological effects of cyclic and direct current, they will be discussed separately. Any form of cyclic electric current, whether alternating or pulsed direct, acts as a nerve stimulus. In standard physiological experiments performed on excised muscles it is possible to demonstrate a muscular contraction for each make and break of the current applied to the controlling nerve fibers (Zoethout and Tuttle, 1946). When a number of such stimuli are applied in rapid succession only incomplete relaxation of the muscle is possible and a condition known as incomplete tetanus develops. Furthermore, if the rapidity of stimuli are increased still more the muscle will maintain a constant state of contraction, or complete tetany. Many years ago, Scheminzky (1924), in laboratory experiments with 20-30 cm. long trout, demonstrated just such tetany, upon the application of 40 volts of alternating current at a density of 0.00893 milliamperes per square millimeter. His description of the reaction is as follows:

> . . . the animals swim around rapidly during switching on, become immediately pale due to pigment contraction, and the breathing stops. . . . A tetanic contraction of the entire body can be seen. If the current is interrupted breathing resumes immediately, at first slowly, but soon a little accelerated and deeper. The pigment cells spread slowly out.

Our experiments, carried out under stream conditions and employing standard electrofishing equipment, have given very similar results. With paddle-type electrodes 13 feet apart and a generator output of 225 volts alternating current, a voltage gradient of 1.6 volts per linear inch was obtained midway between the electrodes.

In this electric field a 10.7-inch male brown trout was placed and held by hand. Use of a rubber glove made it possible to feel the fish's reaction without subjecting oneself to the current or appreciably distorting the electrical field. When the fish was placed at right angles to the lines of current flow, in the mid-field area, no reaction was evident, but, when the fish was turned so as to be parallel to the lines of flow, it was possible to feel a distinct body tremor which lasted for as long as the specimen was held in this position. A repetition of this positioning was made at a distance of 30 inches from an electrode. When a fish was placed at right angles to the field, an initial violent muscular spasm occurred followed by reduced movement but when held parallel to the field complete immobilization of the fish resulted. At a distance of 12 inches from the electrode, and even at right angles to the field, the fish appeared to be immobilized, and, judging from their rigidity, the body muscles seemed to be in a state of complete tetany. Based on these observations of apparent, complete tetany of the body muscles, it would seem highly probable that the cases of vertebral and aortic damage occur as a result of violent, tetanic contractions of antagonistic musculature.

It has been observed that such injuries often occur in situations where the fish are shocked from undercut banks or other exceptionally protective cover, and where, by the quick insertion of an electrode into such an area, the fish have been brought very suddenly into an electrical field of extremely high voltage gradient. We have made a number of efforts to try to reproduce such a situation artificially. Retaining fish of various sizes in a trough, constructed of a standard minnow seine staked out across a stream channel, we have attempted to produce injury by sudden insertion of an electrode close to fish at various positions relative to the electrical field. We have tried this sudden application of the electrode on fish that were induced to violent activity by hook and line irritation exerted on the mouth or the dorsal or caudal fins. We have also tried normal shocking procedure on groups of eight to ten inch fish confined to a 6 feet x 32 feet cement raceway. All attempts thus far have failed to produce the injuries observed in field operations.

As has already been mentioned, numerous cases of mortality have been observed which appear to have resulted from suffocation. The relationship of rapidity of suffocation to oxygen requirements as suggested by Smolian (1944) has been mentioned previously. In an attempt to substantiate the possibility of such a relationship to electric shock, we decided to compare the recovery reactions of a brown trout and a long nose dace, *Rhinichthys cataractae*, which appear to differ considerably in anoxemia toleration. Using the described minnow-seine holding trough and a 225 volt alternating current output producing a water voltage gradient of 1.6 volts per linear inch, a 4.7 inch long nose dace and a 4.6 inch brown trout were subjected to the current for 60 seconds. Both fish were identically oriented in the field. During the period of shock the brown trout breathed spasmodically while the dace ceased breathing. At the end of the shocking period both fish resumed a regular respiration and within a few seconds simultaneously regained their swimming ability. Following a rest period permitting resumption of normal activity, both fish were again shocked with the same strength of current and similar orientation, but for a period of 120 seconds. By the end of this time period both were totally immobilized and the trout had blanched in color. Five minutes after cessation of shock the dace appeared to have completely recovered while the trout, although resuming his normal color, never again respired or otherwise moved. Lack of additional specimens prevented further tests at this time, but one other comparison was made at a later date with laboratory facilities. In a 12 x 30 inch aquarium with a water depth of four inches, and a uniform current density of three volts per inch, alternating current, a 6.8 inch brown trout subjected to shock for 20 seconds never moved again, while a 9.5 inch western long nose sucker partially recovered.

During numerous laboratory experiments carried out on three to five inch carp, their recovery from shock of longer duration and higher voltage gradients has been observed. We cite these data as partial evidence supporting the anoxic toleration concept.

In regard to the causes of anoxic conditions, we believe there may be two closely related reactions, tetany of respiratory musculature and cardiac inhibition. Aserinsky, et al (1954), investigating the effects of various frequencies of direct current stimuli on young salmon, have shown that pulsed direct current, which produces cyclic stimuli, has a markedly inhibiting effect on respiration, while continuous direct current, lacking stimulating qualities, has very little such effect. Furthermore, they were able to show that an increase in current pulse frequency increases respiratory inhibition. If, as investigations seem to indicate, the musculature of a fish does become partially or completely tetanized in a cyclic current field, it seems probable that the subsequent cessation of respiratory movement might, in itself, eventually prove lethal. Coupled with this condition there is very probably an impairment of the circulatory system, which, by means of its contact with the gill filliaments, is a fish's principal means of CO_2- O_2 exchange. Considering the probable physiology involved, it is suggested that the stimulating components of the

17 alternating current act on the vagus nerve which, when so stimulated, may cause a decrease in rate or force of heart beat or even complete cessation (Zoethout and Tuttle, 1946). An additional complication may result from cardiac fibrillation, which is the discordant reaction of the normally concordant heart muscle fibers, and is very apt to occur upon the application of a strong electric current. This condition likewise will produce cessation of circulation. During any such period of coronary failure the flow of blood is impaired and the body tissues are without an efficient O_2-CO_2 exchange. Such impairment of heart action, however, is temporary and despite continued vagal stimulation the heart resumes beating. The vagal impairment of heart action is known as *cardiac inhibition* and the subsequent resumption of pulse is termed *escape from inhibition*.

It was felt that any information on these reactions relative to an electrofishing situation might give a clue to some causes of mortality. With the equipment available it was impossible to observe this sequence of reactions as it would occur in an unharmed specimen. On four occasions observations were made on animals vivisected to expose the pericardial cavity. It must be remembered, however, that it is possible that the reaction of the exposed and unexposed hearts may be quite different. Our first test was made under field conditions with an eleven inch male brown trout. With the fish held belly up in the stream, the pericardial cavity was opened to expose the heart. Upon application of an alternating current field with a gradient of 1.6 volts per linear inch of water, fibrillation occurred regardless of whether the fish was oriented parallel or at right angles to the lines of current flow. In a gradient of 0.33 volts per inch, fibrillation occurred only when the fish was parallel to the field. Following a period of application sufficient to stop all other observable action, it was noted that the heart had resumed a slow but regular pulse which continued regardless of orientation.

The remaining three tests were carried out in the laboratory, using an aquarium with a uniform electrical field having a gradient of three volts per inch of alternating current. The first specimen shocked was a 10.5 inch western white sucker, *Catostomus commersonnii*, vivisected as described. Prior to the application of "shock" the pulse was timed at 1.3 per second and appeared strong. During shock the pulse was reduced to 0.15 per second, and the heart appeared to be in a state of fibrillation. With the cessation of shock the pulse rate rose to 1.0 per second. The next test was made on a 7.3 inch brown trout. The pulse rate was clocked at 2.0 per second before current application and dropped to 1.0 per second for the first 30 seconds of shock. However, after

19 30 seconds the heart commenced a slow, regular beat which continued for the shock duration. With the cessation of current the pulse speeded to 1.5 per second. The final test was made on a 8.3 inch brown trout whose pulse rate prior to shock was clocked at 2.0 per second. During a 20 second shocking period an initial fibrillation was quickly followed by a regular pulse rate of 1.0 per second that continued after shock cessation. These tests seem to give a definite indication of the inhibitory response to cyclic current stimuli as well as the eventual escape from inhibition, but further tests are necessary for a valid conclusion.

It has been previously pointed out that five fish taken with direct current, have shown the vertebral injury usually considered to be typical of alternating current. As a result of those observations, it was decided to try to determine what some of the actual physiological effects of this current might be. Any one who has had the opportunity to work with direct current electrofishing equipment is well aware of the galvanotactic phenomena in which the fish, after initial anodal orientation, swim toward the positive electrode. The actual cause of this type of orientation does not appear to be well understood. Heilbrunn (1943) reviews a number of theories of explanation. For instance it has been considered that the response is related to the vestibular apparatus of the ear, but subsequent work on decapitated fish has shown that the response may still be present. A second theory has suggested the possibility of relationship to the lateral line system, but the response has been demonstrated in animals in which the nerves to this system have been cut. Until recently it was considered that the presence of the spinal cord is necessary for galvanotaxis, but experiments by Haskell, et al, (1954) recorded galvanotaxis in specimens from which the entire central nervous system had been removed. On the basis of the latter tests the investigators postulate that the galvanic stimulation is on the peripheral nerve endings controlling the body musculature in general and in particular that of the caudal peduncle. The orientation effect appears to be almost mechanical.

Following orientation, the fish swim toward the anode, but if retained too long in the electrical field appear to become stunned and drop to the bottom. However, it has often been possible to "lead" fish for distances of over ten feet before all swimming ability ceased. In his early work Scheminzky (1924) considered that the immobilizing effects of alternating and direct currents were similar, but attributed them both to electronarcosis. Subsequent investigations (Scheminzky, 1933) proved that alternating current produced immobilization due to tetanic muscular contracture, and Kraus and Reiffenstuhl

(1933) went on to demonstrate that there is actually considerable difference between alternating and direct current effects. Using animals treated with a solution of caffein, which, with stimuli, produces irreversible muscle contractions, they found that, while alternating current produced such contractions, falling direct current - i.e., head of animal facing anode - had no comparable effect. Furthermore they demonstrated that chemically induced muscular contractions were reduced or dissolved by falling direct current, while rising direct current - head of animal facing cathode - and alternating currents acted to augment them. In these latter findings we begin to see that, there is evidence of a difference in direct current effects according to the orientation of a fish toward the anode or cathode. Further study of this latter comparison was made by Scheminzky (1936) in which he was able to show quite conclusively that rising direct current has stimulating and tetanic effects very similar to those of alternating current.

Prior to our knowledge of the above data, the known instances of vertebral injury and the occasional heavy mortalities observed to occur among fish in the vicinity of our negative electrode, indicated the possibility of a differential in anodal and cathodal effects. In an attempt to verify this, as well as the comparative effects of alternating and direct current, we made a field test similar to that described for alternating current. In an electrical field with a midpoint gradient of 1.6 volts of direct current per linear inch, the respiratory rate of a 10.6-inch female brown trout was only slightly reduced, and no tetanic effects were detected when the animal was oriented facing the positive electrode and within a distance of twelve inches. However, respiration ceased and a tetanic condition resulted when the animal was placed in a similar position relative to the negative electrode.

Subsequently the fish was vivisected and the heart action observed as previously described. In the 1.6 midpoint voltage gradient the pulse remained normal when the fish was held at right angles to the field, and suffered only a momentary check in the parallel position. Within twelve inches of the positive electrode both pulse and breathing appeared quite regular and strong. At the same distance from the negative electrode the pulse was greatly reduced and breathing appeared to cease. Again, in this experiment, we were able to observe the eventual resumption of the heart beat regardless of body orientation in the field. An additional test was made with a 13.2 inch male brown trout, which had been shocked to the point of exhaustion. Insertion of the positive electrode within twelve inches of the animal's head allowed feeble

3 respiration while the negative electrode in the same position produced apparent immobility.

On the basis of these field data it was decided to make similar, but more extensive, investigations in the laboratory. Copper plates, 12 x 5 inches in dimensions, were fitted into each end of a 30 x 12 x 12 inch aquarium, and wired to a direct current system capable of adjustment to produce any desired voltage gradient. The aquarium was filled with water to a depth of four inches, and, the voltage gradient between the electrodes was tested and found to be uniform. The test for uniformity and subsequent voltage gradient determinations were made with a one inch voltage gradient probe attached to a vacuum-tube voltmeter. The fish were held in the electric field by a 6 x 3 inch plastic screen envelope which permitted normal respiration, observation, and orientation, but produced no current distortion. The first series of tests was designed to compare the anodic and cathodic respiratory reactions of rainbow trout having an average length of 3.6 inches. The four fish, in each of the three groups shocked, were subjected to shock during both anodic and cathodic orientation, but in each group the first and third specimens faced the anode first and the second and fourth faced the cathode first. From the assembled data, (Table 6) it is apparent that the fish subjected to a water voltage gradient of 1.0 volts per inch (Group I)

Table 6.--RESPIRATORY RATES RELATIVE TO ANODIC AND CATHODIC ORIENTATION FOR TWELVE RAINBOW TROUT, *SALMO GAIRDNERII*, SUBJECTED TO SHOCK IN A DIRECT CURRENT ELECTRIC FIELD WITH WATER VOLTAGE GRADIENTS VARIED.*

	Group I				Group II				Group III			
Water Voltage Gradient	1 Volt/inch				2 Volts/inch				3 Volts/inch			
Test	A	B	C	D	A	B	C	D	A	B	C	D
Water Temperature (°F.)	65	65	67	68	66	67	68	69	70	70	70	70
Total length of fish in inches	3.8	3.8	3.3	3.9	4.5	3.4	3.0	3.2	3.2	3.9	4.0	3.1
					Respirations per second							
Prior to shock	2.0	2.6	2.4	2.8	2.2	2.9	2.7	2.7	2.5	2.7	2.6	2.9
Fish facing cathode during 90 to 100 seconds of shock	2.0	2.3	2.3	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fish facing cathode after 300 second recovery period	2.3	2.7	2.6	2.7	0.0	2.8	2.3	2.4	0.0	0.0	0.0	0.0
Prior to shock	2.2	2.6	2.6	2.9	2.8	2.9	2.6	2.5	2.8		2.8	
Fish facing anode during 90 to 100 seconds of shock	1.9	2.2	2.3	2.6	1.6	1.7	1.2	1.3	1.2		1.2	
Fish facing anode after 300 second recovery period	2.1	2.6	2.5	2.8	2.2	2.7	2.6	2.4	2.6		2.5	

* In each group, test A and C faced anode first, test B and D faced cathode first.

24 exhibited a noticeable reduction of respiratory rate, but that reduction and recovery appear to be similar for both anodic and cathodic orientation. In Group II, subjected to 2.0 volts per inch, the respiration, during anodic orientation, was slower than that for Group I, but ceased completely during cathodic orientation. Again recovery appeared to be similar in both cases. In a voltage gradient of 3.0 volts per inch (Group III) anodic orientation appeared to further slightly reduce respiration, but still permitted a normal recovery. Cathodic orientation stopped respiration completely and there was no recovery so that an anodic test was impossible for those specimens initially oriented to the cathode.

In the second series of tests the five fish in each group were subjected to only one type of orientation, and all were shocked in a voltage gradient of 3.0 volts per inch (Table 7). Again the data show a reduction of respiratory rate for anodic orientation, and, as in Group III of the first series, cessation of respiration for cathodic orientation. In this series, water temperature appears to introduce an additional influencing factor for it will be seen that, for cathodic orientation, normal recovery occurred at 49° F. while no recovery occurred at 71° F.

A final series of laboratory tests was designed to show the effects of orientation on circulatory pulse

Table 7.--RESPIRATORY RATES RELATIVE TO ANODIC OR CATHODIC ORIENTATION FOR 20 RAINBOW TROUT (SALMO GAIRDNERII) SUBJECTED TO SHOCK IN DC ELECTRIC FIELD WITH A GRADIENT OF 3.0 VOLTS PER LINEAR INCH OF WATER.

	Group I Water Temp.: 71 F. Fish Facing Anode					Group II Water Temp.: 71 F. Fish Facing Cathode					Group III Water Temp.: 49 F. Fish Facing Anode					Group IV Water Temp.: 49 F. Fish Facing Cathode				
Test number	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
Total length of fish in inches	3.3	3.0	3.1	3.7	3.9	3.2	3.4	2.9	4.2	3.6	3.2	4.1	3.5	3.4	3.8	3.5	3.5	4.2	3.6	3.2
	Respirations per Second																			
Prior to shock	2.8	2.8	3.0	2.5	2.5	3.0	2.9	3.0	2.3	2.9	1.6	2.3	1.8	1.7	2.2	1.3	1.7	1.9	1.9	2.2
During 90 to 100 seconds of shock	1.0	1.0	1.4	1.0	0.9	0.0	0.0	0.0	0.0	0.0	0.6	0.7	0.8	1.1	irr.*	0.0	0.0	0.0	0.0	0.0
After 10 seconds recovery period	2.0	1.7	2.1	1.3	1.0	0.0	0.0	0.0	0.0	0.0	1.3	1.7	1.3	1.8	1.7	1.3	1.5	1.6	1.9	2.1
After 400 seconds recovery period	2.8	2.7	2.6	1.3	0.0	0.0	0.0	0.0	0.0	0.0	1.6	1.6	1.2	1.5	1.7	1.4	1.7	1.6	1.8	2.0

* Irregular

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rates. In this series the apparatus was the same, with the exception of two sets of plastic tongs which were used to hold the fish in the field and spread the pericardial cavity for adequate display of heart action. The vivisection was as described elsewhere. Three brown trout, 8.5, 7.5, and 7.9 inches in length, and two western white suckers, 11.5 and 9.8 inches in length, were all subjected to a water voltage gradient of 3.0 volts per inch. In all specimens the pulse rates observed during anodic orientation were approximately twice as fast as those recorded during cathodic orientation (Table 8). When the current was applied during anodic orientation there was in every case a slight reduction of pulse rate from that observed prior to shocking. However, as the tests were designed only for a comparison of anodic and cathodic orientation and as the heart action prior to shock could not be termed normal, the pulse rates for this period are omitted from the data.

There is an additional factor, possibly a lethal one, relative to direct current application which warrants mention at this time. Aserinsky (1954) has shown that the osmoregulatory capacity of young salmon is severely decreased when those animals are cathodically oriented in a direct current field. In a voltage gradient of approximately 2 1/2 volts per inch, the survival times of fish, previously immersed in NaCl solutions, were significantly

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Table 8.--HEART PULSE RATES RELATIVE TO ANODIC AND CATHODIC ORIENTATION FOR VIVISECTED BROWN TROUT, SALMO TRUTTA, AND WESTERN WHITE SUCKERS, CATOSTOMUS COMMERSONNII, SUBJECTED TO SHOCK IN A DIRECT CURRENT FIELD WITH A GRADIENT OF 3.0 VOLTS PER LINEAR INCH OF WATER.

	Brown Trout			Western White Suckers	
Test Number	A	B	C	D	E
Water Temperature (°F.)	71	71	71	72	72
Total length of fish in inches	8.5	7.5	7.9	11.5	9.8
Pulses per second after 2 minutes of shock facing anode	1.3	1.7	1.3	1.0	1.0
Pulses per second after 2 minutes of shock facing cathode	0.6	0.5	0.7	0.5	0.5

26 reduced when the animals faced the negative electrode. Aserinsky has suggested that this reduction may result from the polarizing effects of direct currents which may alter the surface charge of the gill and change the gill surface permeability. An increase in the gill permeability appears to allow the penetration of unusual, even lethal, concentrations of Na ions into the blood stream. As much of Colorado's water is known to contain considerable amounts of Na ion (Clarke, 1924) it would seem very probable that, in these waters, such a gill permeability change might very well have lethal effects.

Chapter V

DISCUSSION

Included in this paper are data designed to assist in increasing the value of electrofishing through a greater understanding of, what appear to be, important mechanical, physical, and physiological relationships.

General observations of the respective effectiveness of alternating and direct currents have indicated that each type is particularly well adapted to specific conditions. From an overall standpoint, however, there appears to be comparable sampling efficiency for equivalent voltages. Pulsed direct current, having both the stimulating quality of alternating current and the galvanotactic effect of direct current (Haskell and Adelman, 1955) may eventually prove to be of even greater usefulness, but its applications to field work have, as yet, been insufficiently explored. For a valid comparison of any current it is important that the relationships of voltages, current capacities, and current cycles be considered.

Nearly any type of an electrode will introduce current into the water, but the size and shape plays an important part in the effectiveness of the electrical field produced. Greater overall effectiveness is achieved through use of electrodes of greater size and surface area which reduce current concentrations and voltage gradients at the electrodes and, at the same time, increase them midway between these electrodes by the greater overall uniformity of the field, thereby improving the shocking power at this point. Still further improvement is possible by placing the electrodes in the stream in such a way that the electrical current flow parallels, as nearly as possible, the stream current flow. With such an orientation, the long axes of the greatest number of fish will be situated so that the fish are subject to the highest possible total voltage. We have constructed electrodes and electrode systems which satisfactorily meet these requirements with little additional inconvenience to operating personnel.

While it is possible that in the waters of some parts of the country the range of electrical resistivity is not sufficiently great to create an electrofishing problem, in Colorado's waters the range includes extremes that are very difficult to shock. The upland waters of the mountains are so low in dissolved solids that electrical resistivity is very high and comparatively high voltages are necessary for a practical shocking voltage gradient. In the lowland, prairie, waters the salinity is often extremely heavy and the resultant electrical conductivity so great that present equipment reaches its amperage capacity at too low a voltage for shocking. We felt that a salinity test, if indicative of resistivity, would be an aid to a more accurate reporting of electrofishing success. Lack of success might then be attributed to something other than lack of fish in the stream. A comparison of methyl orange alkalinity and specific resistance readings showed a fair degree of negative correlation but lacked the desired definition in saline waters. Subsequent comparisons of specific resistance and Versene total hardness readings showed a sharply defined and relatively constant inverse relationship throughout the range of waters tested. There is a considerable variation of resistivity relative to water temperature, and this is not reflected by either hardness test. It appears, however, that waters having approximately the same Versene hardness very probably will have similar specific resistances at equivalent temperatures. If this is true, then, with the aid of a known series of hardness and relative resistance values, useable estimations of unknown specific resistances can be made and related to the capacities of particular shocking units under standardized conditions. It must be realized, however, that the relationship between specific resistances and electrodes will differ with each electrode system according to its conducting surface area.

Present comparative evaluations of the overall shocking efficiencies of alternating and direct currents fail to show a consistent difference favoring either type. General observations seem to indicate that direct current has greater effectiveness in deep, inaccessible, water while alternating current is slightly more useful in water of considerable velocity. During numerous electrofishing operations in which both types of current have been tried in similar stream sections, we have noticed an apparent equalization of efficiency resulting from respective shocking effects. The "leading" quality of direct current makes it possible to extract fish from cover and turbid holes. At the same time those fish which may be in high velocity water, while, still able to swim, can not do so sufficiently well to withstand the water current and, carried from the electrical field, very quickly recover. In an alternating current field the fish are immobilized and, in this condition, often drop to the bottoms of holes or become lodged where they can not be readily seen or netted. On the other hand, a fish's recovery from immobilization is usually not instantaneous, and it is often possible to pick up individuals that have been removed from the electrical field for many seconds. Such is frequently the case in swift waters. Furthermore, possibly because of the tetanic effects of cyclic current or the greater voltage represented by cycle peaks, an alternating current appears to be better able to stop fish in the weakest part of its field.

Admitting the possibility of a greater shocking efficiency for alternating current, it is still necessary to consider the relation of respective physiological effects to the overall electrofishing picture. There is evidence to indicate that alternating current, due to its cyclic nature, is responsible for a greater mortality than is direct current. The cyclic component produces nerve stimuli responsible for impairment of circulation and respiration. Resultant suffocation appears to be an especially common cause of death in fish under twelve inches and may be related to their duration of retention in the electrical field. Larger fish, while subject to these effects, are also often exposed to higher voltage gradients capable of producing violent muscle contractions and subsequent vertebral damage. It has been pointed out that the probable incidence of vertebral injury is not known but may be much higher than generally supposed. Autopsies of numerous specimens, having characteristic external markings, have shown vertebral injury or serious aortic rupture to be present in every case. Furthermore, it has been our experience that, while the known numbers of injured fish may be quite high, the total number of fish with external, shocker, markings is often far higher. Therefore it seems probable that delayed mortality may, in many cases, greatly increase the loss of shocked fish above that presently recognized.

Direct current, particularly at the cathode, can certainly be lethal to fish, but the frequency of injury and mortality appears to be much lower. In a direct current field the fish are narcotized, and, if subjected to this effect for too long a time, may suffocate. For the most part, however, respiratory and circulatory systems appear to continue to function in anodically oriented fish and, as there is no tetanization, body musculature remains flaccid and vertebral injuries infrequent. On the basis of the comparative physiological effects of direct and alternating current it seems probable that the latter's advantage in efficiency is often overbalanced by its greater lethality, which may assume extremely important proportions in populations of large fish.

Suggestions for further study. -- Beyond any doubt electrofishing is a valuable addition to the investigational techniques of the sport fishery. With it fish may be studied in previously inaccessible areas, but it is a new tool and, like any new tool, not completely functional until fully understood. This study is primarily a review of some of the important relationships which may be involved in any electrofishing operation. Field experience has emphasized the need for a better understanding of these relationships, and a subsequent review of literature has pointed to the comparatively unused information source provided by the fields of physics and physiology. It is hoped that our endeavor to elicit some of this material and attempt its practical application to the problem may serve to show the need for a much more detailed study of all electrofishing aspects.

From our observations it appears that there is a need for a much more exact understanding of the role of the electrical resistance of water relative to temperature and concentrations of dissolved solids. Possibly the proposed use of the Versene test may provide an aid in obtaining some of these data, but the universal validity of this use remains to be specifically determined. In the light of our present knowledge it seems obvious that standard electrofishing equipment is distinctly limited in the range of water resistivities to which it may be successfully applied. This fact points to an entirely new line of endeavor to include the development of apparatus adjustable to specific operational needs, with particular emphasis on increased effectiveness in highly electrically conductive waters. Prior to such development a further study of the practicability of conforming operations to fit seasonal conditions may prove to be of value.

In commercial fishing or trash fish removal, the damaging effects of electric current on fish may not be of primary importance, but in sport fishery work, they are paramount, as dead or sick fish are of little use to the fisherman. Prior to any extensive development of direct current equipment for saline waters it would be desirable to determine to what degree polarizing currents may produce mortality in such waters, due possibly to gill surface depolarization as suggested by Aserinsky (1954). Of a more academic nature but still necessary to a complete understanding of galvanic current applications, is the need for a determination of the specific cause or causes of galvanonarcosis.

The physiological relationships producing cyclic current injury and mortality are understandable, but a better knowledge of the stream situations in which they occur might improve the chances of prevention. With the recognition that some seriously injured fish may partially recover and continue to live in a crippled condition, it would be very desirable to ascertain the effect of such crippling on the fish's reproductive capacity. Above all other considerations, however, is the need for a more exact determination of the total incidence of injury and mortality.

Chapter VI

SUMMARY

1. A comparison of the electrofishing efficiencies was made of 230-volt alternating and direct current generators. General and specific effects were noted for two types of waters.

2. The general efficiency of each current was calculated to be approximately the same for a given water type, but the efficiency of both was considerably higher in the stream sections than in the pond sections. Each current was observed to be especially adapted to particular stream conditions.

3. Two types of back-pack shocking units were tried and evaluated, and the principal requirements for practicability relative to weight, voltage, and amperage were noted.

4. A pair of electrodes for stream use was developed on the basis of effective electrical field requirements and general utility. Tests and general field use proved these to be satisfactory for both alternating and direct current applications.

5. Operations using two positive probe electrodes and an intermediate negative, proved very successful in extending the span of the electrical field and improving its orientation for more effective shocking.

6. Field operations were facilitated by the development and utilization of some accessory equipment. This included a set of long-handled electrodes for deep water use, a 500-feet capacity cable reel with a sliding electrical contact, and the use of a two-man rubber life raft for generator transport in deep water.

7. Standard electrical testing apparatus for field work included a battery-operated volt-ohmmeter, which proved useful for checking voltage outputs and general trouble shooting, and a vacuum-tube voltmeter, which was used, with a probe, to measure voltage gradients in both direct and alternating current fields.

8. A wide variation in the specific resistances of Colorado waters was recorded and inversely correlated to the concentrations of dissolved solids present. Total alkalinity and total hardness tests were compared as possible simple indicators of specific resistance, and the latter appeared to show a reasonably consistent relationship to specific resistance readings. A practical method of checking or estimating electrofishing effectiveness appears to be provided by the comparison of total hardness and water temperature readings to known specific-resistance, equipment-capacity, relationships.

9. Some possibilities were noted for offsetting the adverse electrical conditions of excessive conductivity or resistivity.

10. A comparison of the lethality of 220 and 160-volt alternating currents and 220-volt direct current was made and demonstrated a higher mortality for alternating currents. Alternating current produced frequent vertebral injury in large fish and suffocation in smaller ones (under twelve inches) both effects apparently resulting from cyclic current stimulation. Several instances of partial recovery from vertebral injury were recorded, and it was observed that the suffocating effect appeared to vary according to species toleration of anoxemia.

11. Field and laboratory studies were made on the effects of various electrical situations on pulse and respiration. In the field studies, alternating current was found to produce a markedly greater impairment of these functions than direct current. Laboratory comparison of the effects of anodic and cathodic orientation in a direct current field showed a greater reduction of both pulse and respiration during cathodic orientation.

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