THESIS

THE DEVELOPMENT AND EVALUATION OF INTERRUPTED DIRECT CURRENT ELECTROFISHING EQUIPMENT

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY MAX DEAN ROLLEFSON

ENTITLED THE DEVELOPMENT AND EVALUATION OF INTERRUPTED DIRECT CURRENT ELECTROFISHING EQUIPMENT

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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Chapter I

INTRODUCTION

The field of fisheries management has long been in need of adequate sampling devices for study of fish populations. While electricity may be employed to catch, divert, and kill fish, the advantages and limitations of electricity for these purposes have not always been recognized. Since experiments in taking whales in 1881 (Meyer-Waarden, 1957), the other uses of electricity in fish management have developed. Electrofishing has become an accepted technique by many conservation agencies in North America. Permanently installed fish screens at hydroelectric power dams in Western North America have been utilized to divert salmon[1], *Oncorhynchus* spp., from dangerous areas. Applegate, Smith and Nielsen (1952) describe electric fish screens employed in the Great Lakes Region to kill parasitic sea lampreys, *Petromyzon marinus*. Meyer-Waarden (1957) comments on efforts in Germany to control the undesirable Chinese crab, *Eriocheir sinensis*, by means of electrical barriers. Whereas catching and diversionary devices depend upon electric shocks of sub-lethal intensity for effectiveness, a barrier device is meant to stop or kill intended species by a concentrated electric field.

1/ Common and scientific names are those recognized by the American Fisheries Society (1948). See Literature Cited.

The use of electricity in water necessitates a system of metallic conductors, commonly termed electrodes, by which the current is transmitted through the water. Electrodes are mobile for electrical fishing and arranged permanently across a water course to serve as an electric fish screen. Various electrode designs have been described, and a choice seems to depend upon specific requirements.

Both alternating current and direct current available from domestic power lines, batteries, and motor-driven generators have been used to energize electrode systems. An alternating current field produces a muscular tetany. Fish remain semi-active in a direct current field and are drawn to the anode or positive electrode where they lie flaccidly paralyzed. Recently certain investigators have experimented with pulsed currents, which are physiologically more effective in producing galvanotaxic response. As a consequence of current pulsation power economy is achieved. Undulating currents distinguished by a direct current with a super-imposed, high frequency alternating current also have been studied to a lesser extent. Effects on fish of this type of power are similar to those caused by alternating current.

Of significance to the reactions of fish in an electrical field are voltage and current. The two quantities are associated intimately, and a voltage increase or decrease is accompanied by a proportionate change in circuit voltage and current. For a given voltage between two electrodes, current is greater in hard conductive water and less in soft resistant water. The voltage divided by the current is a measure of electrical resistance, or dissolved electrolytes and suspended materials. Also to be considered is the water temperature, because current carrying capacity of water is improved by an increase in temperature. These relationships are of primary importance. Voltage, current and water temperature interact to determine field intensity and exert an influence on recovery of fish and other aquatic organisms from electric shock.

Wide variations in water resistivity of streams complicate electrical fishing operations in Colorado. Jackson (1955a) has described typical experiences in this connection. Electric current control in conductive water poses a problem, and in contrast, the resistant water of mountainous regions serves as an insulator to an electric current. Jackson suggested that current pulsation might reduce power demands in conductive water, and because of the greater physiological effect, result in better electrical fishing success in resistant water.

Because carp, Cyprinus carpio, are undesirable fish, means are sought to prevent their reintroduction into rehabilitated reservoirs. Of most concern here are the inlets to reservoirs which lead to other carp infested waters. If an electric barrier were used in such a location in an attempt to kill carp, it must be almost instantly effective. Otherwise, water flow would carry the fish out of the electric field and into the reservoir. For feasibility, Jackson (1955b) made the stipulation that 100 per cent mortality must occur in a period of ten seconds or less. He experimented with capacitor discharges up to 1,200 volts per linear inch of water delivered at four second intervals in attempts to kill carp. Voltages of this magnitude killed carp oriented perpendicularly to the electrodes in the specified time but were ineffective in producing 100 per cent mortality of those parallel to the electrodes.

Problem

Can pulsed current be produced practicably so as to enhance electrofishing results? What are the individual effects of alternating voltage and current on induced mortality of carp?

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

1. Can an auxiliary unit for pulsed current be constructed and maintained?

2. From a viewpoint of power economy and trout response, what is the optimum pulse repetition rate?

3. What are the advantages and limitations of interrupted direct current electrofishing equipment in resistant streams and conductive streams of large and small size?

4. What are minimum lethal exposure periods for carp under different conditions of voltage and current?

Delimitations.--The study was limited to the period of June 1, 1956, to January 1, 1958. A mechanical direct current interruptor was constructed and evaluated under laboratory and field conditions. Duty cycle and pulse shape were fixed. Optimum pulse repetition rate was determined with trout as test specimens in a specially constructed tank. Experiments were performed at the Bellvue Hatchery near Bellvue, Colorado. Paddle type electrodes with 250 square inches of conducting surface were employed in the field study. Efficiency comparisons of pulsed direct current, direct current, and alternating current upon fish collection were made in streams of northeastern Colorado. A 16-gallon aquarium equipped with one-quarter inch mesh hardware cloth electrodes was used to simulate an electric fish screen. Carp electrocution experiments were conducted on the Colorado State University Campus.

<u>Definition of terms</u>.--<u>Duty cycle</u> refers to the ratio of circuit closure to the length of the cycle.

<u>Pulse shape</u> is the geometric voltage outline at time of circuit closure.

<u>Specific resistivity</u> refers to a measurement of dissolved and suspended materials that conduct an electric current.

<u>Galvanotaxis</u> refers to the forced movement of fishes to the anode when exposed to a direct current field of sufficient intensity.

Chapter II

METHODS AND MATERIALS

Electrofishing experiments

Fish shocking tank.--A fish shocking tank, Figure 1, patterned after the one described by Taylor (1955) was designed and constructed for controlled tests. This was built from three-quarter inch exterior plywood supported by an angle and channel iron framework. Outside dimensions of the tank are 12 feet by 4 feet by 2 feet in depth. The inside of the tank was painted with rubber-based, non-conducting paint. One-quarter inch mesh hardware cloth was used for electrodes which almost covered the ends of the tank. Physical contact of test specimens with electrodes was prevented by means of a plastic screen. The tank was used at the Bellvue Hatchery where fish could be held for experiments. A water depth of one foot was maintained during tests. Domestic power is available nearby.

Pulsating unit.--Considering the means by which a direct current can be interrupted, a mechanical design was chosen in preference to an electronic circuit. It was believed that a mechanical device would prove more reliable and less troublesome under rigorous field conditions. The pulsating unit (Figs. 2 and 4) was constructed from a Ford starter motor, utilizing the case and commutator shaft. The armature was cut off to reduce weight. With a shorting bar across the commutator, it was possible to create a regular sequence of

Figure 1.--Fish shocking tank and various electrical equipment employed in the controlled galvanotaxic experiments.

Figure 2.--The pulsating unit mounted on a panel for field tests.

Figure 3.--Paddle electrodes, dip net, and collapsible live box utilized in stream electrofishing experiments.

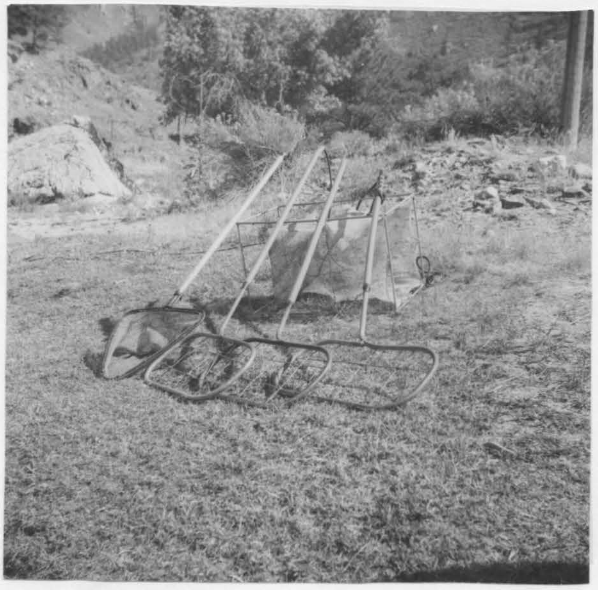
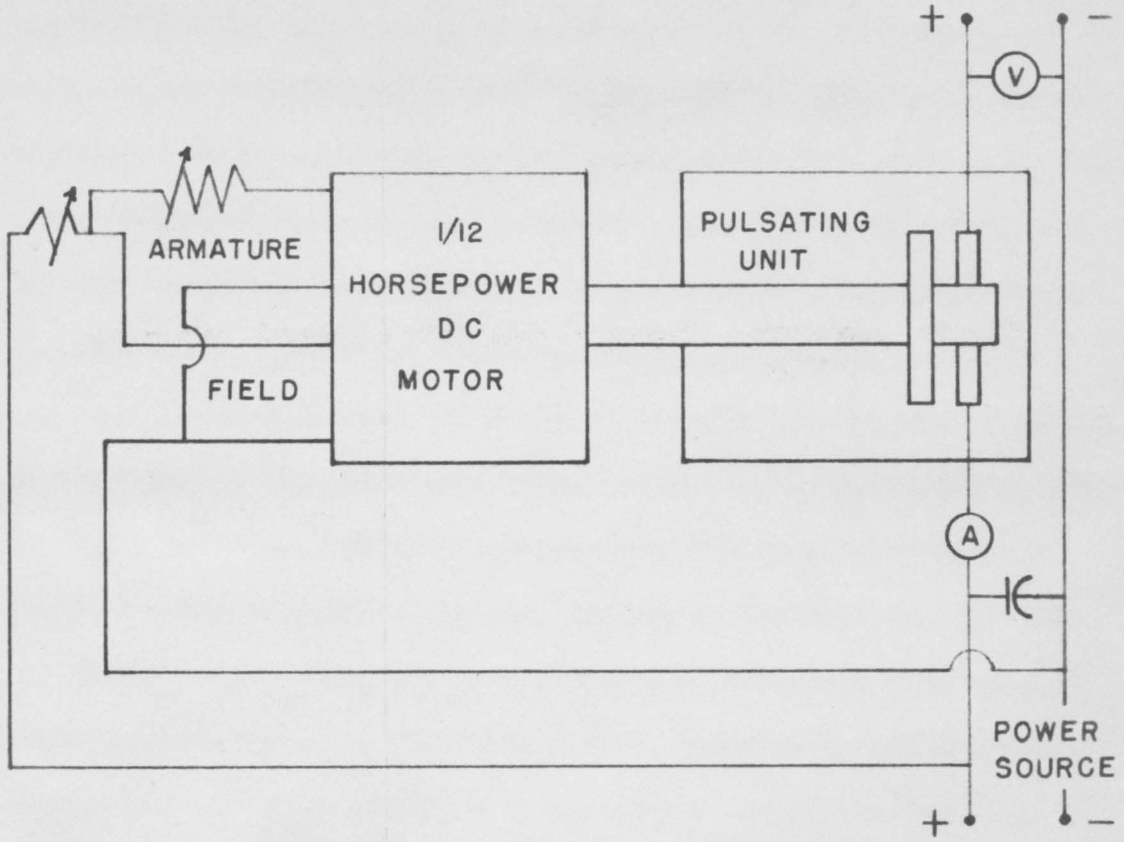
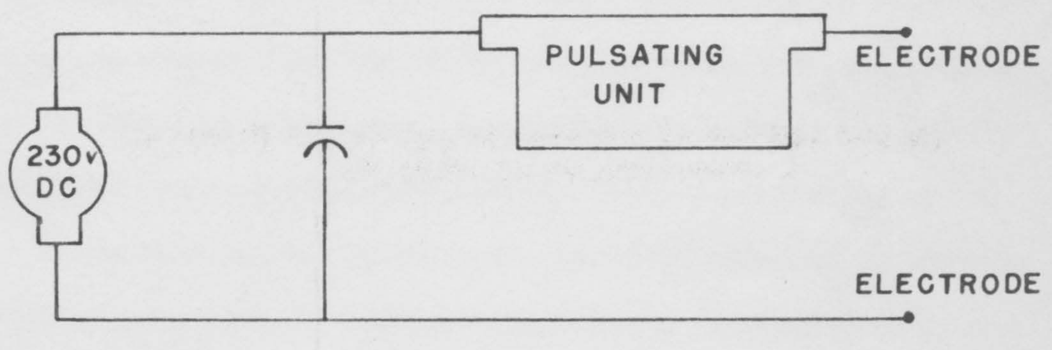


Figure 4.--Circuit diagram of the direct current pulsating unit.

Figure 5.--Circuit employed in pulsed direct current electrofishing experiments.



VARIABLE SPEED DIRECT CURRENT INTERRUPTER



CIRCUIT EMPLOYED FOR PULSED DIRECT CURRENT ELECTROFISHING pulses by rotating the shaft. By varying the number of commutator segments shorted together on opposite sides of the commutator, a variation in pulse width, or duty cycle, could be effected. For experimental work, either two or four generator brushes were used. The commutator-brush assembly was driven by a direct current motor, the speed of which was varied by means of a rheostat in the armature of the motor. This pulsating unit also may be seen in Figure 1.

Pulse shape was basically rectangular in outline. However, an electrolytic 125 microfarad capacitor was necessary to reduce arc at higher voltage. Capacitor storage and discharge resulted in a peaked leading edge with a gradual decline to the trailing edge of the pulse. Pulse shape was more peaked and protracted with conductive loads than with resistive loads. Capacitance and arc were responsible for this feature of pulse shape. Voltage control was essential for electrofishing operations in conductive water so as not to damage the commutator.

Although other pulse shapes have been studied in respect to galvanotaxic experiments, the rectangular pulse was selected because it was the simplest to achieve. Loukashkin and Grant (1954) reported on five wave forms of pulsating current. These included the square pulse; triangular pulse; the half-wave rectified alternating current; the quarter wave rectified alternating current, characterized by an abrupt peak with a slow decay; and a condenser discharge. The authors did not differentiate these wave shapes relative to their efficiency. They seemed to believe that current density was the important variable. Meyer-Waarden (1957) seems to prefer the pulse shape produced by a condenser discharge for anodic attraction. The various pulse shapes discussed are illustrated in Figure 6.

Duty cycle was set at 35 per cent. This choice was influenced by the findings of Taylor (1955) who determined that a duty cycle of 33 per cent was more efficient in eliciting galvanotaxic response than either 47 per cent or 88 per cent duty cycles. He also pointed out the power economy that results from a reduced duty cycle. Due to the unavoidable conditions described above duty cycle increased noticeably with more conductive loads. Current interruption in an oil bath would alleviate this discrepancy.

German electrofishing equipment.--A German impulse generator was secured from Utah State University to ascertain its utility for electrofishing. This device was powered by a 12-volt battery. Voltage output was variable by means of a hand switch from about 150 volts to 250 volts direct current. Viewed on an oscilloscope, a choice of two voltage wave forms was available. Positions one through four produced a square wave, and positions five through nine yielded a triangular wave form. Pulse frequency was about 60 cycles per second. With a 12-volt battery, the unit weighed about 70 pounds. Electrodes consisted of an energized dip net as the anode and a rectangular mat as the cathode which was extended on the stream bottom.

Electric power sources.--In addition to storage batteries and domestic 110 volt alternating current, the following power sources were used for various purposes during the study:

Gasoline generators

Voltage	Watts
230 VDC	2,500
230/115 VAC/DC	2,500
115 VAC	1,000
115 VAC	150

Ballantyne dynamotor (Battery operated)

500 VDC	80

Battery eliminator

0 - 12 VDC

Electrode systems.--An electric seine and paddle electrodes were used in the field evaluation. Copper floats and pendant shielding cable constituted the electrodes of the electric seine. Almost all of the field data were collected using the paddle type electrodes similar to those described by Jackson (1955a and 1956). These are shown in Figure 3. Conducting surfaces of the paddle electrodes are about 250 square inches. Depending on the current limitations of the power source and the number of available personnel, two or three electrodes were employed. If three electrodes were used with direct current, the two outside ones were positive so as to exploit the galvanotaxic effect. Although voltage remained the same, provided there was no overload of the generating equipment, current was increased about 33 per cent by the inclusion of a third electrode. A spool with sliding contact, described by Jackson (1955a) facilitated

Figure 6

(Voltage wave forms)

A Square wave form of pulsed direct current.

B Triangular wave form of pulsed direct current.

C Half-wave rectified, 60-cycle alternating current.

D Quarter-wave rectified, 60-cycle alternating current.

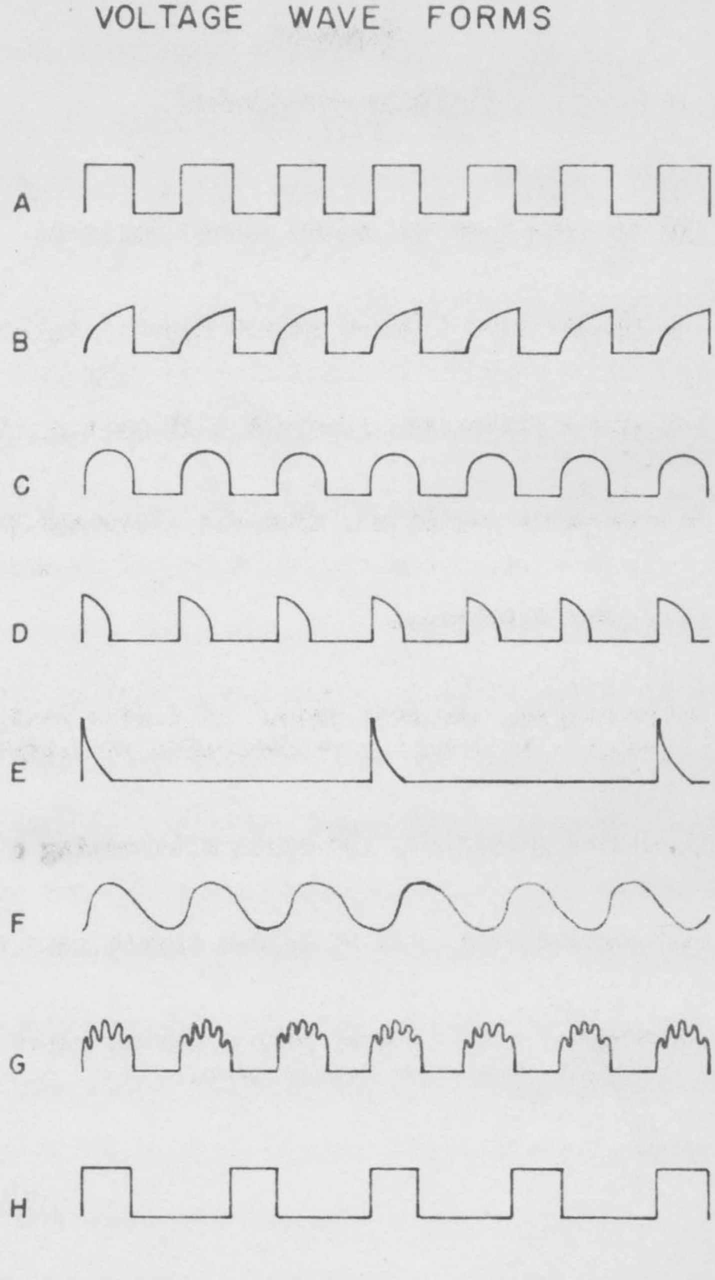
E Condenser discharge.

F Round-topped, sawtooth wave. Half-wave rectified, 60-cycle alternating current with capacitance.

G Half-wave rectified, 180-cycle alternating current.

H Rectangular wave form of pulsed direct current.

I Rectangular wave form of pulsed direct current, abruptly peaked by capacitance.


VOLTAGE WAVE FORMS
A
B
C
D
E
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I

cable storage. Simplex-Tirex, two conductor, #18 cable rated at 600 volts was used. The techniques described by the above author were used in electrofishing operations.

Other electrical equipment.--Direct current generator control was accomplished by means of field rheostats. Alternating voltage was regulated by a variac. Measurements of voltages were made with a Heathkit vacuum tube voltmeter or a Simpson voltohmeter. These meters also were used in checking circuit continuity. Ordinarily an ammeter was placed in the line to determine direct current flow through the water. Peak voltages and duty cycle were noted on an oscilloscope. Revolutions per minute of the motor driven current interruptor, and hence pulse repetition rate, were determined mathematically with the aid of a strobotack or tachometer. Specific resistivity of water samples was calculated periodically from measurements made with an Industrial Instruments conductivity bridge. These assessments were corrected to the standard temperature of 77°F., unless water temperature is explicitly mentioned.

In the case of interrupted direct current, both current and voltage were recorded as average values. These measurements were usually about 35 per cent of steady direct current measurements, depending upon the degree of arc.

Fishing equipment.--Fish were collected with dip nets and retained in live boxes. Where necessary, fish were fin-clipped for identification and measured to the nearest 0.1 inch. Stream conditions dictated the use of barrier seines. One-eighth and three-eighths inch mesh seines were employed where barriers were judged necessary.

Electrocution experiments

Carp supply.--Carp utilized in the electrocution experiments originated in the Windsor Reservoir System, about four miles northeast of Windsor, Colorado, and in the Timnath Irrigation System about two miles northeast of Timnath, Colorado. Fingerling fish were collected by seines and electrofishing equipment, although the great majority were captured in small minnow traps. Some of the carp from the Windsor Reservoir System were retained at the site in a stock tank. About 5,000 carp of this group were transferred to a small pond in Fort Collins, Colorado. The carp from the Timnath Irrigation System were utilized at the termination of the electrocution experiments.

Facilities.--With the exception of a few tests performed in the Forestry Building, the remainder of the electrocution experiments were conducted in the Electrical Engineering Laboratory at Colorado State University. Since alternating current is usually available and can be transformed to higher voltages, it was selected in preference to direct current. A transformer and induction voltage regulator permitted a selection of voltage levels from 115 volts to 450 volts. Voltmeters and ammeters were used to measure voltage and current.

A 16-gallon aquarium rigged with one-quarter inch mesh hardware cloth electrodes was used to simulate an electric fish screen. Shocking media included Windsor canal water, pond water, and tap water to which salt solution was added to increase current density. Temperatures and specific resistivities of the shocking medium were recorded frequently.

Prior to shocking, carp were kept in water to which they were accustomed. Preliminary experiments indicated that fish resistivity to an electric current was changed perceptibly by immersion in tap water of about 7,632 ohm-centimeters at standard temperature. Therefore, carp and water for holding purposes were secured simultaneously. Test specimens were dropped into the aquarium without regard to orientation relative to the electrodes. Lethal exposures were timed with a stop watch. Following exposure, carp were removed with a small dip net, marked by fin removal for later recognition and observed during a recovery period in tap water. This was changed frequently to ensure adequate oxygen supply. Survivors were shocked repeatedly until 100 per cent mortality resulted.

Chapter III

PRESENTATION AND ANALYSIS OF DATA

Because of the dual nature of this study, the results are presented in separate parts. The first portion to be discussed deals with the method of electrofishing. This technique is used by many conservation agencies to acquire fish samples from streams for various purposes. The second portion relates to the deliberate electrocution of carp.

Electrofishing

Major objectives within the scope of this portion of the project included the following:

1. Design and construction of a suitable direct current interruptor for electrofishing.

2. Satisfactory laboratory performance with various resistive loads that simulated electrofishing operations.

3. Determination of optimum pulse repetition rate for galvanotaxic response. Responses of trout were emphasized particularly, since they are the foremost game fish in Colorado.

4. Electrofishing comparisons of pulsed direct current, equivalent direct current and alternating current in streams of northeastern Colorado.

5. Detection of fish mortalities due to utilization of the above forms of power.

6. Laboratory and field study of a German electrofishing apparatus.

Laboratory study of a direct current interruptor

Several possible means of interrupting a direct current were considered initially. The decision to use a mechanical interruptor in preference to an electronic device was based upon the advice of Professor John E. Dean, Head of the Electrical Engineering Department. The device utilized was described in detail in Chapter II. Initially two types of mechanical devices were tested, *viz.*, a distributor and a commutator-brush assembly. These devices were tested in the laboratory relative to their ability to handle current loads at different direct current voltages. A variable capacitor, to reduce arc, was used in parallel with the resistive load to determine the size of capacitor necessary for field tests. Because of the larger contact surface for current conduction, the commutator-brush assembly was selected, modified, and perfected for the purpose. Figure 4 is a diagram of the circuit employed in the field studies.

Controlled galvanotaxic experiments

Interrupted direct current.--After satisfactory laboratory performance of the pulsating unit had been achieved, galvanotaxic experiments were begun at the Bellvue Hatchery. The fish shocking tank (Figure 1) was used for these tests. Hatchery water ranging in specific resistivity from 1,980 ohm centimeters to 2,390 ohm centimeters at 77°F. was used. Water temperature extremes due to changeable weather were 56° and 66°F. Water changes were made frequently to bring about more desirable temperatures and to ensure adequate oxygen for the test animals.

The immediate objective of the galvanotaxic experiments at the Bellvue Hatchery was to select the most efficient pulse repetition rate for the anodic attraction of trout. From the literature it is apparent that the importance of the pulse repetition rate has been recognized by other workers.

Loukashkin and Grant (1954) state that control of fish movement can be obtained with any pulse frequency from 2 to 80 pulses per second. Haskell and Adelman (1955) seem to favor slow pulse repetition rates for galvanotaxic effect. Taylor (1955), utilizing rainbow trout, _Salmo gairdnerii_, determined that 96 pulses per second produced optimum results. Because of these differences, it seemed desirable to test this entire range of repetition rates.

Using rainbow trout and brown trout, _Salmo trutta_, 14 pulse repetition rates were tested. The range studied was from one pulse per second to 145.2 pulses per second. Within each frequency of interruption, several voltage levels were applied to tank electrodes to assess trout responses. Sufficient resistance was placed in the generator field so that steady direct current voltage across the electrodes could be varied from 60 to 220 volts. For the two lowest frequencies, a variable direct current power source, 0-12 volts, was used across the armature, with 115 volts applied to the field of the one-twelfth horsepower direct current motor. For the other repetition rates, the armature voltage of the direct current motor was varied by means of a rheostat which controlled armature current and motor speed. Except for the single pulse per second which was timed by a stop watch, the motor speed, and hence the repetition rate, was adjusted by means of a strobotack.

After a repetition rate had been selected and the necessary adjustments made, the voltage across the tank electrodes was reduced by a field rheostat to the minimum possible level. Ordinarily this consisted of 10 to 20 volts average value. A trout then was placed in a small hardware cloth cage in the center of the tank. A cord from the cage across a pulley made it possible to release the fish as desired. Upon release of the fish, the circuit was closed and timing of the reaction commenced.

Two methods of evaluating fish responses were tried initially. Attempts to time reactions during three reversals of electrode polarity proved fruitless. Although a few specimens responded to a single reversal of polarity, trout ordinarily were paralyzed at the original positive electrode. This technique was used by Loukashkin and Grant (1954). The categorical responses used by Taylor (1955), similar to those described by McLain and Nielsen (1953), were tried subsequently and adopted. This method consists of a timed exposure of fish to a direct current field during which their reactions are observed carefully.

Table 1.--CATEGORY AND DESCRIPTION OF RESPONSE OF TROUT TO A DIRECT CURRENT ELECTRIC FIELD.

Code	Description
0	No polarity or distress.
1	Shivering and signs of minor distress.
2	Fair galvanotaxis. Immediate movement to positive electrode at initial shock, but usually escaped.
3	Strong determined movement to positive electrode. No paralysis in less than seven seconds.
4	Complete paralysis in six seconds or less. Usually fish did not reach positive electrode.

Preliminary tests indicated that code numbers listed in Table 1 did not describe adequately the observed responses. Therefore a plus or minus was added to the code number, depending on the observed response. If a fish made a confused circle in the tank upon circuit closure after which it moved immediately to the positive electrode, the response was categorized code 3-. If a fish promptly moved to the positive, became less active and did not paralyze in seven seconds, it was assigned a 3+. If a fish tended more toward paralysis, but remained semi-active up until seven seconds had elapsed, the response was judged a 4-. For statistical purposes, a 3- was allotted a value of 2.66, and 3+ was assigned a value of 3.33. Other values were established in a similar manner. For evaluation of trout responses, a 3- and 3+ were regarded within the optimum range of galvanotaxic performance.

Sixty-four trout were utilized in these tests, of which eighteen were kept separately as control fish. Sixty were large hatchery rainbow trout and four were brown trout of similar size. Employing direct current, 144 performance trials were run during a period of nine days. Following each trial, the fish were measured and marked by the removal of a fin. Periodically the fish were sorted as to experimental quality. Initially the cumulative number of different marks was considered. Later, quality was judged on the basis of body slime and general vigor. A control fish was used when confirmatory evidence was desired. Preliminary experiments indicated that lower voltages produced a 1 or 2 response and higher voltages resulted in a 4 or 4- response. Where the observed response differed noticeably from the expected, another trout was exposed to the same voltage intensity.

Table 2 indicates that the favorable range of pulse frequency was from 76.6 pulses per second to 124.8 pulses per second. Inasmuch as the lowest volt-ampere characteristic was reached at 95.2 pulses per second, this repetition rate was selected for further experimental work. With exception of the single pulse per second, power requirements for all repetition rates were less than for steady direct current. Volt-ampere requirements for optimum trout responses at 95.2 pulses per second were about 6.7 per cent of direct current requirements for the same response. Volt-amperes were calculated by multiplying average voltage by average current.

Table 2.--COMPARISON OF 14 DIRECT CURRENT PULSE REPETITION RATES RELATIVE TO MINIMUM AVERAGE VOLTAGES AND AVERAGE VOLT-AMPERES REQUIRED FOR OPTIMUM GALVANOTAXIC RESPONSE OF TROUT.

Number of pulses per second	Minimum average voltage	Average volt-amperes
Steady DC	62	26.7
1	90	48.6
15	50	14.0
29.8	40	11.2
58.6	30	7.2
67.4	30	6.6
76.6	20	2.6
86.0	20	3.0
90.0	20	3.0
95.2	15	1.8
100.0	20	3.0
104.0	30	6.3
114.4	20	2.8
124.8	20	2.6
145.2*		

* An optimum response was not achieved at this repetition rate.

The data in Table 3 are presented to indicate whether or not a conditioning response to electric shock occurred. The performance trials of these fish were conducted separately. Where possible, attempts were made to use fish of nearly equal length. A "t" test of the difference between mean code responses for the two groups was not significant. It appears that the results were not unduly influenced by the fact that some of the specimens were shocked more than once.

Table 3.--COMPARISON OF RESPONSES OF SHOCKED AND UNSHOCKED TROUT TO EQUIVALENT ELECTRIC FIELDS IN THE FISH SHOCKING TANK.

	Specimen shocked previously		Control fish		
Average voltage	Code Response	Fish Length	Code Response	Fish Length	Repetition Rate
10	1	9.2	1	9.1	86.0
20	3	8.9	4	9.5	124.8
30	3-	9.0	4	9.5	67.4
30	4	11.3	4	10.5	124.8
30	4	9.1	3	8.9	100.0
30	4	10.2	3	8.8	90.0
40	4	10.7	3	10.5	76.6
40	3+	9.2	3+	10.2	95.2
40	4	9.2	4	10.4	100.0
40	3	9.1	3	8.5	90.0
50	3	9.9	2+	9.8	15.0
50	4	9.5	4	8.6	95.2
70	3+	10.0	4	10.6	104.0
Mean -	3.33	9.63	3.28	9.61	

Half-wave rectified alternating current.--Alternating current may be transformed and rectified to direct current. These two qualities render alternating current a distinct possibility for direct current electrofishing. Half-wave rectification results in a 50 per cent duty cycle and round-topped pulses at the frequency of the power source (Figure 6). Thus it was desirable to determine the utility of half-wave rectified alternating current.

Eight tests were performed with domestic power using a 350 miliampere selenium half-wave rectifier in series. With the negative portion of the sine wave removed, responses of trout to five voltage intensities were studied. It appeared that with a voltage wave of this nature and 60 cycles per second, average pulsed values of 40 volts and 11.6 volt-amperes were necessary to cause an optimum response.

Another series of tests employing half-wave rectified 60-cycle alternating current was performed. The circuit remained the same except that a small capacitor rated at 80 microfarads and 150 volts was placed in parallel with the resistive load. Five voltage intensities were applied to the tank electrodes and the performances of ten trout studied. Viewed on an oscilloscope, the voltage wave with capacitance was a round-topped sawtooth wave with limited "off-time." Average pulsed values of 40 volts and 10.8 volt-amperes were required for optimum response with this wave shape. The next eight tests were conducted with half-wave rectified 180 cycle alternating current. With this frequency of current interruption, a critical field intensity was reached at 30 volts and 7.2 volt-amperes, upon which galvanotaxis occurred.

These results provide an interesting comparison to those presented in Table 2 for interrupted direct current. Sixty-cycle power requirements for galvanotaxis were about one-third greater than for interrupted direct current at similar frequencies. Requirements for 180 cycles per second were the same as those for 58.6 pulses per second. In view of the additional power requirements with alternating current, pulsed direct current of 95.2 pulses per second was preferable for field tests.

Influence of current density on galvanotaxis.--To determine the effect of increased current density on galvanotaxis, salt was added to the tank in small quantities. Fifty-three trout were used in these tests. A repetition rate of 95.2 pulses per second was employed. During the experiment, the average pulsed voltage level was maintained at 30 volts, while current density was increased by 0.1 to 0.2 ampere increments. Trout responses to the electric field tended irregularly toward paralysis as currents were increased. However, this occurred over a relatively wide range. Current was increased from 0.2 amperes to 1.4 amperes in 11 steps. Performance trials suggested that a moderate increase in current density improved fish response. Between one ampere and 1.4 amperes, the paralytic response was noted in 12 out of 16 test fish. Such a response indicated over-control of fish movement and implied a voltage reduction so as not to cause undue mortality.

At the termination of the above experiment, the voltage intensity was reduced to the minimum possible level. This voltage reduction was effected for a comparison of fish responses at similar low voltages with different repetition rates. With a potential of nine volts and a current density of 0.35 amperes, four trout were exposed to the electric field. The responses of these four trout signified over-control. While one trout exhibited a code 3 response, the others were judged 4-. For comparison with this experiment in three other trials at various repetition rates, where trout were exposed to fields of 10 volts and 0.06 to 0.08 amperes of current, their responses were characterized by shivering and signs of minor distress or code 1 response. In a previous test using steady direct current of 12 volts and 0.48 amperes, a 12-inch trout was unaffected by the electrical field. The four trout in the above test reacted anodically and were narcotized or paralyzed by an average volt-ampere relationship of 3.15 volt-amperes. In contrast, the application of of 5.76 volt-amperes of steady direct current to the electrodes produced a code 0 response for a 12-inch trout. These experiments seem to emphasize the importance of current density to direct current electrofishing and tend to confirm the existence of an optimum range of water resistivity where direct current electrofishing may be practiced. In addition, current pulsation resulted in galvanotaxis with lower power consumption.

The average length of 57 trout, including four brown trout and 53 rainbow trout used in these experiments, was 10.4 inches. The range was 4.6 inches and the standard deviation was 1.03 inches. Several trout died during the tests and shortly afterwards, but the cause of death could not be associated with any particular form of treatment. Deaths might have been caused by handling.

Interpretation of results.--A duty cycle of 35 per cent and an abruptly peaked rectangular voltage pulse shape were utilized in the galvanotaxic experiments employing interrupted direct current. An optimum pulse repetition rate was sought that would result in minimum power requirements for anodic attraction of trout. Since the intensity of an electric field around an electrode in the water decreases infinitely with each increment of distance from the electrode, the largest elliptical range of effectiveness is desired

(Haskell, 1954). This is particularly true for resistive streams where direct current electrofishing loses its effectiveness. Although more data are necessary to isolate the most effective repetition rate within the optimum range of 76.6 to 124.8 pulses per second, the frequency of 95.2 pulses per second is a good choice for the purpose of further experimentation. This frequency is near the midpoint of the optimum range. Moreover, Taylor (1955) determined under similar conditions that 96 pulses per second was the optimum repetition rate for the galvanotaxic response of rainbow trout. Quantitative increases in current density indicated that voltage levels could be reduced as water conductivity increased.

Field tests

Fish collection.--Following termination of experiments at the Bellvue Hatchery, necessary apparatus for an auxilliary unit to the 230 volt direct current generator was mounted on a panel (Figure 2). The motor for the interruptor could be operated in parallel with the resistive load by means of rheostats, or operated independently from an alternating current source. Where the latter was used a full-wave rectifier provided necessary direct current for motor operation. Because of its less fragile construction, a tachometer replaced the use of a strobotack in adjusting repetition rate.

In view of controlled fish shocking tests, it seemed probable that the operating range of the 230 volt direct current generator was increased by current pulsation. To what extent this assumption was true for various waters of this region was the subject of ensuing investigation. This work is discussed from the standpoint of the two extremes in water resistivity. Special consideration was given to the possibility of pulsed current for electrofishing in broad and/or deep pools. Experience in resistive streams is reviewed first. Unless specified otherwise, differences in potential are 230 volts. For brevity the abbreviations AC and DC will be used in this discussion. Stream section lengths are paced distances.

Resistive streams.--Initial tests were performed in Buckhorn Creek, a small headwater stream west of Fort Collins, tributary to the Big Thompson River. A short section of stream about 250 feet in length was shocked three times on July 5. The first trip with DC yielded one rainbow trout. The second sweep with pulsed DC of 85 volts and 0.1 amperes yielded five trout. These fish collected with DC were apparently unaffected by the electric shock. All fish recuperated, were marked by fin removal, and returned to the stream section. A third trip with AC through this section produced twelve trout, three of which were captured previously with pulsed DC. Relative to fish loss, one brook trout, Salvelinus fontinalis, of 2.9 inches total length was killed by AC and another 3.8 inches long appeared in critical condition. Lengths of fish taken here ranged from 2.9 inches to 9.5 inches.

Another section of this stream was shocked several days later with the same sequence of currents. Six fish, ten fish and fifteen fish respectively, were collected on successive sweeps through this section. As before, AC proved the most efficient form of current for fish collection here. However, two trout not collected previously on this date were killed by AC. Both were brook trout. One was 8.6 inches in length, the other 3.5 inches long. Relative to DC, the interrupted current was superior to steady current. No fish mortality occurred with DC. Barriers on this stream consisted of short riffles; in one case a beaver dam constituted the downstream terminus of a section.

Collection of spawning suckers, *Catostomus* spp., in the East Inlet to Grand Lake permitted additional study of these currents. East Inlet is a moderately swift deep stream, and in places is difficult to wade, particularly during spring runoff. These data were collected July 18, 1957. A specific resistivity of 75,128 ohm centimeters at 45°F. was recorded here. Pulsed DC and AC were used and unquestionably, the latter form of power was superior. Pulsed DC of 85 volts and 0.14 amperes was not sufficient to immobilize the fish. An electric seine as well as three paddle electrodes were tried here. Clearly the paddle electrodes were the more efficient of the two systems.

Buckhorn Creek tests indicated a superiority of pulsed DC over steady DC, but pulsed DC was inferior to AC. The results in the East Inlet to Grand Lake clearly pointed out the deficiency of a pulsed DC of 85 volts in respect to 230 volts AC. It should be noted that 230 volts AC refers to an effective value. Peak voltage is actually 325 volts ($230 \times \sqrt{2}$). The cyclical nature of AC and this peak voltage effect were thought to be the reason for the better success with AC. It was apparent from these tests that additional current was essential for successful DC electrofishing.

Because current flowing between electrodes may be increased by an increase in the voltage applied, a Ballantyne direct current dynamotor rated at 0.16 amperes and 500 volts was incorporated into the equipment for soft, resistive water. Using a 6 or 12 volt battery, this dynamotor puts out a peak voltage of about 400 volts and 0.2 amperes. If the current drawn is greater than 0.2 amperes, the voltage drops off correspondingly. The rated output of this unit is 80 watts, whether it is delivered as voltage or current. The dynamotor was used in connection with a storage battery in the same manner as a power plant and the output interrupted by the pulsating unit. By using the dynamotor, average DC voltage and current were nearly doubled. A second electrolytic 125 microfarad capacitor rated at 250 volts was necessary to handle the additional voltage.

Four-hundred volts DC was used first in Pennock Creek, a tributary of the Little South Fork of the Cache la Poudre River. Widths of this stream vary up to 30 feet; maximum depth is about five feet. Here, a section of stream about 350 feet in length was selected for a comparison between 230 volts pulsed DC, 400 volts pulsed DC and 240 volts AC. Terminal boundaries of this section were satisfactory natural barriers. The downstream barrier was a small concrete dam used for irrigation and the upstream terminus was a beaver dam. The first run with 230 volts pulsed DC, average values of 85 volts and 0.1 amperes, yielded ten trout which were marked and released. The second trip with 400 volts pulsed DC, average values of 150 volts and 0.2 amperes, yielded 38 trout which also were marked and released. Twenty-eight fish were subsequently collected with

240 volts AC. One of these, a 7.4 inch brown trout, did not recover from the shock. This fish had been taken previously on the first sweep with 230 volts pulsed DC.

For further evidence of the hypothesis that higher DC voltages could be used advantageously in electrofishing, a series of three tests were made on three sections of Pennock Creek. These tests were conducted August 4, 10, and 19, 1957. Sections 1, 2, and 3 were respectively about 675, 625, and 525 feet in length. As part of their summer camp instruction, some of the Colorado State University Forestry students at Pingree Park participated in these tests. Table 4 summarizes the catches of fish made in these tests. Sweeps with 220 volts pulsed DC and 240 volts AC were made with three electrodes, and runs with 400 volts pulsed DC were made with two electrodes.

Table 4.--NUMBERS OF TROUT COLLECTED FROM THREE SECTIONS OF PENNOCK CREEK WITH ELECTROFISHING EQUIPMENT EMPLOYING THREE VOLTAGE INTENSITIES.

Voltage	220 pulsed DC	400 pulsed DC	240 AC
Section 1	29	88	58
Section 2	40	110	79
Section 3	22	55	61
Total	91	253	198

The results in Table 4, which shows the number of trout collected from Pennock Creek with three voltage levels, were examined by means of the statistical technique, analysis of variance. The "F" value for voltage levels was significant at the 95 per cent confidence limit. The "F" value of 16.18 would occur in only one sample out of 20 such samples as this, if the results with different voltage levels were due strictly to chance. A single degree of freedom comparison of the two DC voltages against the AC voltage was not significant. On the other hand, a comparison of the two DC voltages was highly significant. The "F" value was 31.29. This is significant at the 99 per cent limit of confidence.

The "F" value for DC voltages indicates that higher voltage is imperative to effective DC electrofishing in resistive streams. Results with 400 volts pulsed DC and 240 volts AC were not significantly different. On the basis of trend, further increase in DC voltage might result in proportionately more effective fish sampling with DC electrofishing equipment.

On two occasions, August 4 and 19, all fish collected in Pennock Creek were taken to the Forestry Summer Camp where they were held overnight in a live box. The following morning the survivors were carefully examined for marks and injuries and returned to the section of Pennock Creek from which they had been captured. Total lengths, species and marks of dead fish were recorded. Overnight mortalities and the observed dead at the time of shocking during all three tests are recorded in the following table:

Table 5.--COMPARISON OF THREE VOLTAGE LEVELS AND TROUT MORTALITY RECORDED IN PENNOCK CREEK.

Group	Voltage	Number captured	Number dead	Per cent dead of total captured	Average length
1	220 DC	91	1	1.1	6.8
2	400 DC	253	12	4.7	3.4
3	240 AC	198	1	0.5	3.6

Table 5 seems to indicate the danger associated with higher voltages. It should be noted that average size of the dead fish was about 3.6 inches. Not uncommonly, these small fish were not noticed until they were in close proximity to the electrodes. This exposed them to an intense field, and probably resulted in heavy paralysis. Death is believed due to suffocation, (respiratory paralysis) heart failure, or both.

That danger to fish is increased by utilizing higher voltage is conceded. On the basis of evidence presented in Table 5, mortality may be increased by factors of four to nine by the application of 400 volts DC to the electrodes. Because of optimum anodic response with this voltage, there was a natural tendency on the part of electrode operators to seek out fish lying in out-of-the-way places. Some of these areas harbored the young fish that seemed particularly vulnerable. The use of such voltage obviously must be accompanied by caution. Nursery areas, i.e., shallow backwater areas, for small fish probably should be avoided, unless mortality of fish is of minor consequence. Care probably should be exercised when proceeding into large pools where there is risk of increased turbidity. It appears that such pools should be shocked carefully so as to immobilize a few fish at a time, removing them promptly to safety. Under conditions of these tests, a second catching electrode probably would have reduced voltage requirements for effective work. Voltage control to reduce field intensity is necessary to minimize fish mortality. However, no voltage regulation was possible in this instance, and the use of three electrodes would have caused an excessive overload of the dynamotor.

For further evidence of the efficiency of 240 volts AC compared with 400 volts DC, two time trials were conducted in the Little South Fork of the Cache la Poudre River. This stream is smaller than the East Inlet to Grand Lake, but the water approaches the specific resistivity of this stream. When these experiments were run, the specific resistivity was about 58,989 ohm centimeters. Water temperature was 52°F. It was necessary to time the experiments here because stream width and size did not permit a complete span of the stream. The technique used consisted of working cover near either side of the stream with two electrodes. When a time period had elapsed, the power was changed and shocking upstream resumed.

Of these fish only one was killed. It was a brook trout 1.8 inches in length, and death probably was due to suffocation. It was killed on the second trial with 400 volts DC.

Table 6.--NUMBERS OF TROUT COLLECTED FROM THE LITTLE SOUTH FORK OF THE CACHE LA POUDRE RIVER EMPLOYING TWO VOLTAGE INTENSITIES.

Date	240 volts AC	400 volts DC	Time
7/30/57	8	13	30'
8/20/57	22	32	60'

The Chi-square test of homogeneity was applied to these data. Average values for each sequence of tests were used as the best estimate of expected values. The computed Chi-square value of 3.02 leads to rejection of the hypothesis of a real difference in efficiencies of DC and AC. However, the probability of a chance Chi-square this large or larger is about 22.5 per cent. Hence, this is weak evidence in favor of higher DC voltage for electro-fishing.

After high water had subsided, tests were begun on the Cache la Poudre River. The first site to be studied was the section of stream immediately below the dam at the mouth of Poudre Canyon. This work was performed August 23, 1957. This section might be categorized as a moderately large stream. Volume of flow was about 400 cubic feet per second. Stream width varies up to 100 feet, and water depths extend to six feet or more. At this point, it is still relatively low in electrolytes. Resistivity was 16,691 ohm centimeters at the standard temperature. A two-man rubber raft was used here to haul the generator and pulsating unit. The area was shocked first with steady DC voltage maintaining a ten foot spread as nearly as possible. A "path" was selected that seemed to hold the most promise of fish. Three small fish were collected on the first trip. A subsequent run following the first course with pulsed DC yielded ten fish, one of which died. Although this experiment indicated the advantage of current interruption, another point was affirmed. It is essential to place an electric field about a fish in order to immobilize and collect it. Attempts to orient the field from a rubber raft were abandoned as futile. The conclusion was reached that where water depth did not permit wading, an ineffective sampling of the fish population was the result. Recognizing the inadequacy of available electrode systems, further effort to evaluate current pulsation in large waters was suspended.

Recognizing equipment limitations for the lower Cache la Poudre River, suitable side channels were sought where tests might be performed. A section of stream near Mishawaka was sampled with both 240 volts AC and 400 volts pulsed DC. Neither form of power was found well-suited for fish collection work under the conditions that existed in this location. Therefore higher voltage and current were judged to be necessary. Utilizing a second dynamotor in parallel with the first resulted in an average increase of 40 volts and 0.06 amperes. The results were still unsatisfactory.

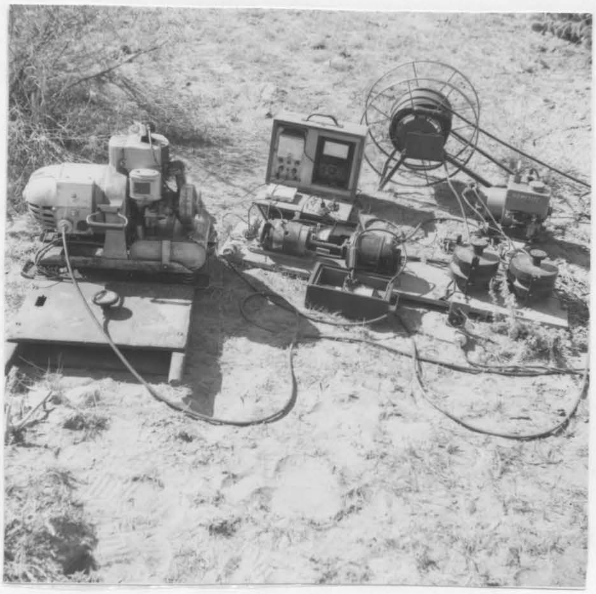
A third dynamotor was added to the generating equipment and tested September 11, 1957 on a side channel near Sportsman Lodge. Work near Mishawaka was discontinued because of wading difficulties.

Water resistivities at the two locations were similar. With three dynamotors, averaged pulsed voltage was 205 volts and 0.30 amperes. This was an average increase of 5 volts and 0.04 amperes. Before the storage battery was drained of its charge, 18 fish were collected, measured and returned to the stream unharmed. The same section of stream was shocked with 240 volts AC the following day. Nine fish were collected on this trip, one of which did not recover. This was a 10.3 inch brown trout. Chi-square for these data is 3.00. This value is significant at the 91.5 per cent level of confidence. This was the only test conducted where a DC voltage of this magnitude was applied to the electrodes. It should be noted that this was accomplished without injury or mortality of fish.

Conductive streams.--Toward the other extreme of water resistivity, two experiments were run on the North Fork of the Cache la Poudre River. Here, specific resistivity was about 6,127 ohm centimeters. Electrofishing success with steady DC and pulsed DC was compared during the first test. About 300 feet of stream below Seaman Dam was shocked. Since the first run with steady DC yielded only six fish, a second sweep with pulsed DC was made immediately afterwards. Average potential and current were 20 volts and 0.9 amperes respectively. This time 55 fish were collected despite a broken cable that ended the experiment before the upstream boundary was reached. About 40 linear feet of the section were not shocked with pulsed voltage. A longnose dace, *Rhinichthys cataractae*, a white sucker, *Catostomus commersonii*, and a brown trout failed to recover from narcosis.

Figure 7.--Some of the electrical equipment employed during the electrofishing experiments.

Figure 8.--Electrofishing in the Cache la Poudre River.



A nearby section of stream about 200 feet in length was shocked on another occasion. Sixteen fish were collected with steady DC. Before the sweep with pulsed DC, captured fish were released singly in an effort to determine optimum pulsed voltage. Electrodes were held about ten feet apart, a fish dropped between them, and the fish response observed. Voltages of 130, 150, 160 and 180 were tried and the latter selected. At the lesser voltages, there seemed to be some escape from the field between electrodes. Eighty-four fish were collected during the sweep with interrupted voltage. Four trout, 7.7 inches to 16.0 inches total length, and one western white sucker were killed. Apparently a lesser voltage should have been employed here.

Perhaps fish loss could have been mitigated in the previous two tests by the application of lower pulsed voltages. Clearly, caution in voltage selection is indicated by these tests. Unquestionably, the tests indicated the superiority of pulsed voltage. Homogeneity Chi-square for the pooled results was 85.00, which is significant at the 01 per cent level of confidence. Water temperature of the North Fork of the Cache la Poudre River during this period was about 73°F. Stream flow approximated 10 cubic feet per second. The above tests were performed August 9 and 12, 1957.

A section of the Cache la Poudre River near Timnath, Colorado, typifying hard, conductive water was selected subsequently for study. September 5, 1957, specific resistivity was about 1,226 ohm centimeters at 70°F. Steady DC of 63 volts resulted in anodic attraction, although fish response was improved by the application of 127 volts. The former potential probably approximates the minimum steady voltage for such locations. The current measured for this potential was 5.6 amperes. Pulsed values of 36 volts and 1.18 amperes, resulted in comparable efficiency. The duty cycle was 26 per cent during this test. Why this is true cannot be explained satisfactorily. Whether commutator brushes were making poor contact, or whether it was some other mechanical or electrical phenomenon, can not be asserted. In any event, this voltage and duty cycle resulted in anodic attraction. Tentatively, power economy seemed to be the only advantage of pulsed current here. Additional work with a 35 per cent duty cycle should be performed to determine whether or not interrupted current of this nature has advantage over steady equivalent DC voltage. Necessary interrupted current was about 12 per cent of the steady DC power. An abundant coarse fish population facilitated this experiment. No fish mortalities were observed here.

To substantiate the hypothesis that lesser pulsed voltages could be employed in moderately hard waters, a series of tests was conducted in several streams harboring trout as well as less desirable species. The streams selected for this purpose included the Laramie River, North Platte River, Michigan River and North Fork of the Cache la Poudre River. All streams were comparatively low, clear, and presented nearly ideal electrofishing conditions. These experiments were performed during the period September 11 through September 28, 1957. Steady DC voltages, average pulsed voltages, average pulsed current, and water resistivity appear in Table 7. Average voltage and current should be considered as approximate and indicative of the optimum levels at which satisfactory fish collections can be made.

Table 7.--STEADY DIRECT CURRENT VOLTAGES AND AVERAGE PULSED VOLTAGES AND CURRENTS REQUIRED FOR OPTIMUM FISH RESPONSE IN FOUR STREAMS.

	Steady voltage 1/	Average pulsed voltage	Average pulsed current in amperes	Specific resistivity ohm centimeters
Laramie River	120	38	0.24	5,717
North Platte River	110	33	0.32	4,126
Michigan River	90	30	0.30	3,301
North Fork Cache la Poudre River	90	30	0.34	4,124

1/ Voltage measured before current interruption.

Suitable pulsed currents were established by making several sweeps through a stream section, increasing the voltage if necessary. For example, in a section of the North Platte River, an average voltage of 26 volts and 0.22 amperes was tested first. This was found ineffective and voltage was increased to 33 volts. The average current was 0.32 amperes. This intensity seemed to be sufficient. For comparison, voltage was increased to 48 volts where current was 0.44 amperes. The number of fish captured remained the same. The additional power apparently did not increase efficiency.

Moderately convincing evidence of a differential response of suckers and trout to an electric field was observed in the North

Fork of the Cache la Poudre River. White suckers and longnose suckers, Catostomus catostomus, were affected slightly by a pulsed current of 19 volts and 0.25 amperes while brown trout were unaffected. An increase to 23 volts and 0.30 amperes brought about better anodic attraction and narcosis of suckers, but trout were able to leave the positive electrode and the electric field. Moving into shallow, fast water, it was apparent that the latter potential was not adequate to immobilize the trout. When field intensity was increased to 30 volts and 0.34 amperes trout responded to the positive electrode and were recovered easily with a dip net. Length ranges of these two groups were similar. This differential susceptibility to electric shock might be employed deliberately in the capture of suckers from comparable stream locations.

To conclude the series of tests in conductive water utilizing pulsed DC and equivalent steady DC, a section of the Cache la Poudre River near North Shields Street Bridge was shocked. The length of the section was 400 feet. Beginning on a riffle, electrode operators proceeded upstream to a large pool immediately below a culvert. Specific resistivity was 6,571 ohm centimeters.

The first sweep with a steady current of 225 volts and 1.95 amperes yielded 96 fish of various species. The following day, a run through the same section with a pulsed current of 90 volts and 0.95 amperes produced 314 fish, with minor exception indicating the same species composition. It should be noted that these values approximate a 40 per cent duty cycle relative to generator voltage output. Not uncommonly the duty cycle increased to a small extent due to greater current loads at higher voltages. Arcing could be reduced by voltage reduction, but for this test, voltage was left intentionally at the maximum level. Quantitative evidence of added physiological stimulation and the associated mortality figures were desired. Of 314 fish collected, at least 36 perished, and it is entirely possible that other unobserved mortalities occurred. Of this total, 75 per cent of the fish were less than five inches in length. Thus, pulsed current yielded a larger fish sample, but about 11.5 per cent of the fish died presumably due to suffocation and heart failure. This test vividly emphasized the need of voltage control.

Fish mortality and injury.--Jackson (1955a) has discussed in detail certain factors associated with mortality of fish when subjected to an electrical field. Under simulated natural conditions at the Bellvue Hatchery, he determined mortalities of equal numbers of rainbow trout collected with 220 volts DC, 220 volts AC and 160 volts AC. The latter voltage is an effective value; it is the peak or maximum voltage divided by the square root of two. Hence, maximum AC voltage is approximately comparable to 220 volts DC. Trout mortalities recorded over a seven day period were 30 per cent for DC, 55 per cent for 220 volts AC, and 40 per cent for 160 volts AC. These percentages indicate that a certain mortality can be expected with either DC or AC current, and possibly AC is the more dangerous to fish. Moreover, higher voltages perhaps may cause higher fish mortalities.

Although it would not be justifiable to project these results to electrofishing in natural stream conditions, limited mortality probably can be anticipated with either form of power. As an example of fish mortality under natural conditions, of a total of 284 trout and whitefish, Prosopium williamsoni, collected during a population study on a Wyoming stream during 1956, four whitefish died after DC electrofishing. This mortality definitely can be ascribed to the operation, but cause of death cannot be related positively to shock. Human handling of fish in dip nets may have had an effect on the observed mortality.

During the present study, 1,660 fish were shocked and examined closely during field tests. This figure includes only those fish captured and retained in live boxes for comparatively brief periods. Observed mortality was 66 fish, or 3.47 per cent of the total. Although immediate cause of death was not established, mortality probably was due mainly to paralysis of the respiratory system and heart failure. About 55 per cent of this mortality was incurred deliberately to emphasize the danger in excessive voltage. Clearly voltage control is essential to allay excessive mortality.

A few examples of vertebral separation were noted, but detailed information relative to their occurrence is lacking. External black markings characteristic of internal hemorrhage and injury were noted on six fish collected in Pennock Creek. Walch (1949) has called attention to this type of shocker injury, and Jackson (1955a) has examined and described carefully the trauma that sometimes occurs. Without exception these marks were found on the posterior one-half of the body. Three fish were collected with 400 volts DC and three fish with AC. To what extent these injuries were incapacitative was not determined. Following a retention period of about 16 hours, the fish were returned to Pennock Creek. Jackson (1955a) cites evidence that some shocker injuries may heal properly and produce little permanent debilitation. Three out of five injured brown trout retained for about 18 months were in the latter category. The other two showed definite weight loss and physical impairment. In view of his findings, not all fish with this type of internal injury are lost to fishermen.

Electrode systems.--Limited comments regarding electrode arrangements are warranted. The electric seine described briefly in Chapter II was employed on two occasions. This device can be visualized as a floating rubber cable to which are attached alternately in parallel four-inch by five-inch ellipsoidal copper floats and one-half inch shielding cables four feet long. There are four floats and five pendant shielding cables separated by five foot intervals. One and one-half inch poles on either end facilitate movement of the 50 foot seine. According to theory, electrical field intensity is limited near the distal ends of the shielding cables due to the fact that electricity takes the path of least resistance. Hence, the effective field probably is restricted to the immediate vicinity of the surface of the water. Results in the resistant water of East Inlet to Grand Lake were unsatisfactory. The seine was given limited trial in the moderately hard water of the North Fork of Cache la Poudre River. Here also the seine was inferior to paddle electrodes. Moreover, electrolysis along the uppermost six inches of pendant electrodes suggested that electric current was not evenly distributed throughout the area between shielding cables and the copper floats. Electrodes of equal length might serve to improve the electric field. Perhaps a certain amount of rigidity would tend to eliminate field concentration but changes in water depth would complicate mobility. No further work was done with this device.

A technique that might have merit in pools too deep to wade was tried on the North Fork of Cache la Poudre River. A length of number 12 wire was stretched across a pool and anchored by rocks in midstream. The wire was connected to the negative terminal of the generator and a paddle electrode was fished on either side of it. Two sweeps through this pool utilizing this arrangement yielded 22 fish. In contrast two runs through the same area with a negative and positive electrode yielded 10 fish. The former method is advantageous in that it allows two catching electrodes.

Because much of the field work was carried out by two men, it was advantageous, particularly for DC electrofishing, to determine whether a second catching electrode would produce larger fish samples than those obtained with a single positive electrode. By permanent location of the negative electrode, two catching electrodes can be utilized. Two evaluations of such a nature were performed.

The first test was conducted on the Cache la Poudre River near Timnath, Colorado. Specific resistivity was 2,162 ohm centimeters. Steady DC of 225 volts was employed in this test. An iron stake driven into the stream bank to a depth of about 13 inches served as the negative. Two positive electrodes were fished in the vicinity. One creek chub, Semotilus atromaculatus, was turned or seen briefly with this arrangement. Utilizing the conventional system of a negative and positive paddle electrode, several suckers and creek chubs were noted. Current drawn by the former arrangement was about 2.4 amperes with two positive electrodes immersed. With the conventional ungrounded arrangement, a current of 4.6 amperes was recorded. The latter system was preferable since field orientation was in a horizontal plane between electrodes. The circuit with a grounded negative was through the stream bottom to a point beneath each electrode. Therefore, the effective electrical zone surrounding each positive electrode probably was limited, as indicated by electrofishing results.

The second test employing a stationary negative electrode was conducted in Pennock Creek. The specific resistivity was 24,205 ohm centimeters. An average pulsed voltage of about 80 volts was employed in this experiment. The first run through the 350 foot section of stream with a negative and positive electrode yielded ten trout which were marked and released. Submerging the negative electrode near the generator, a second sweep through the same section was made with two positive electrodes. This run produced six trout. Although fish were stimulated throughout this run, trout collections were not made until the positive electrodes were within 15 feet of the negative electrode. This test indicated that long electrode spans weakened field intensity to the extent that fish were not narcotized.

Since a stationary negative electrode did not seem to offer any advantages, further consideration of the arrangement was abandoned. Two mobile electrodes, a negative and positive, were employed in subsequent field tests.

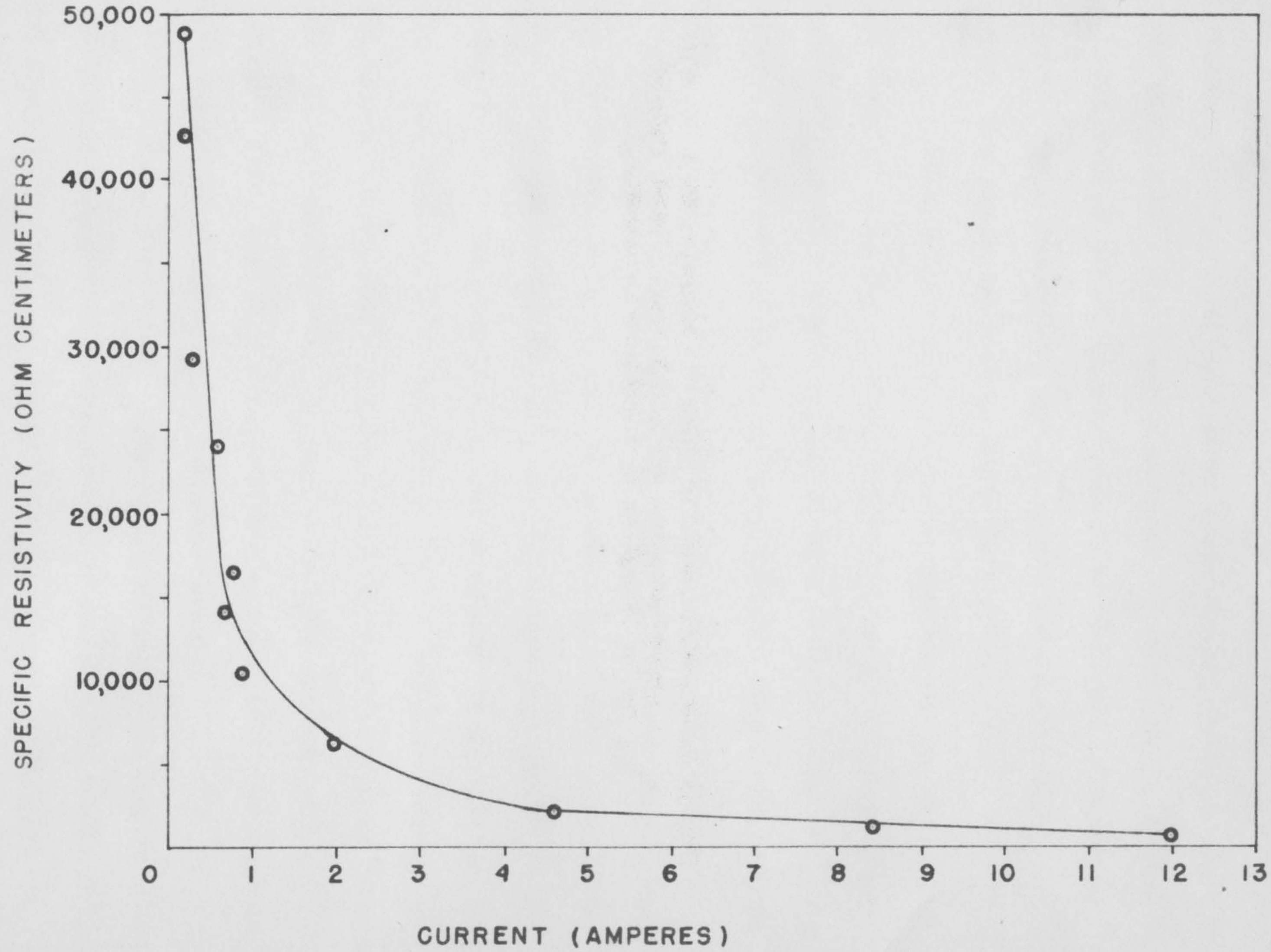
Before continuing, it seems appropriate to recapitulate the information accumulated during the field tests. All relevant data were collected with paddle electrodes of 250 square inches conducting surface. Pulsed direct current was compared with 240 volts alternating current in stream areas where specific resistivity exceeded 16,692 ohm centimeters. From this upper limit to 1,110 ohm centimeters, pulsed direct current was compared to the equivalent, or greater steady direct current voltage. Current pulsation was accomplished by the motor-driven commutator brush assembly described in Chapter II. The duty cycle of generating equipment employed was approximately 35 per cent. A repetition rate of about 95.2 pulses per second was used throughout the field tests.

Because of its galvanotaxic properties, direct current perhaps is preferable to alternating current for electrofishing. Results with 230 volts pulsed direct current in resistive waters indicated that to achieve efficiency comparable to that of alternating current, direct current voltage had to be increased. Table 8 and Figure 9 show how currents drawn by the electrodes described above vary with changes in specific resistivity. To effect greater currents in resistive water, it was necessary to increase voltage levels. One, two, and finally three dynamotors in parallel rated at 500 volts and 0.16 amperes provided the means by which suitable electric fields

Table 8.--SPECIFIC RESISTIVITIES AND CURRENTS DRAWN BY TWO ELECTRODES WITH 195 TO 230 VOLTS DIRECT CURRENT AT 11 LOCATIONS IN NORTH-EASTERN COLORADO.

Location	Date	Specific resistivity in ohm centimeters at 77°F.	Currents in amperes
Cache la Poudre River (Three miles south of Windsor)	8/30/57	691	12.0
Cache la Poudre River (Timnath)	9/5/57	1,110	8.4
Cache la Poudre River (Timnath)	7/22/57	2,162	4.6
Cache la Poudre River (North Shields Street)	9/7/57	6,571	1.95
Colorado River (Camp Ouray Bridge)	7/19/57	10,792	.88
Colorado River (One mile downstream from Granby Dam)	7/19/57	14,159	.62
Cache la Poudre River (Mouth of Poudre Canyon)	9/23/57	16,692	.74
Cache la Poudre River (Poudre Ponds)	9/3/57	24,560	.52
Pennock Creek	8/19/57	29,754	.22
Little South Fork of the Cache la Poudre River	8/20/57	42,746	.16
East Inlet to Grand Lake	7/18/57	49,036	.12

Figure 9.--Specific resistivities and currents drawn by two electrodes with 195 to 230 volts direct current at 11 locations in northeastern Colorado.


50,000
40,000
30,000
20,000
10,000
SPECIFIC RESISTIVITY (OHM CENTIMETERS)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
CURRENT (AMPERES)

could be established in resistant waters. Generating equipment did not permit comparison of steady direct current voltage and interrupted voltage. However, a pulsed voltage that averaged 205 volts and 0.30 amperes provided a sufficiently intense electrical field to indicate a superiority of pulsed direct current over 240 volts alternating current. Water resistivity was 42,343 ohm centimeters during these tests. The stream temperature was 50°F.

Table 8 and Figure 9 indicate that current is ample at low resistivities. As a matter of fact, since the water is such a good conductor of electricity, one of three courses of action is required. A generator with sufficiently high current capacity may be used. As alternatives to this, electrode size may be reduced, or a field rheostat may be employed to reduce generator voltage across the electrodes. Of the three alternatives, the latter seems preferable. At a resistivity of 1,110 ohm centimeters a potential of 63 volts of steady direct current on the electrodes provided an adequate electrical field for fish collection. At this voltage a current of 5.6 amperes was recorded. A pulsed direct current voltage of 36 volts and 1.18 amperes of current provided comparable electrofishing success. Power used with pulsed voltage amounted to 12 per cent of that required with steady direct current voltage.

Table 9 and Figure 10 indicate graphically how specific resistivities vary over a 78 mile stretch of the Cache la Poudre River. The altitude of Station 0, about three miles south of Windsor, is approximately 5,000 feet; the elevation of Station 78 is about 8,200 feet. Station numbers correspond to the estimated stream mileages from Station 0. Maps of the area were used to make estimates of distances and altitudes.

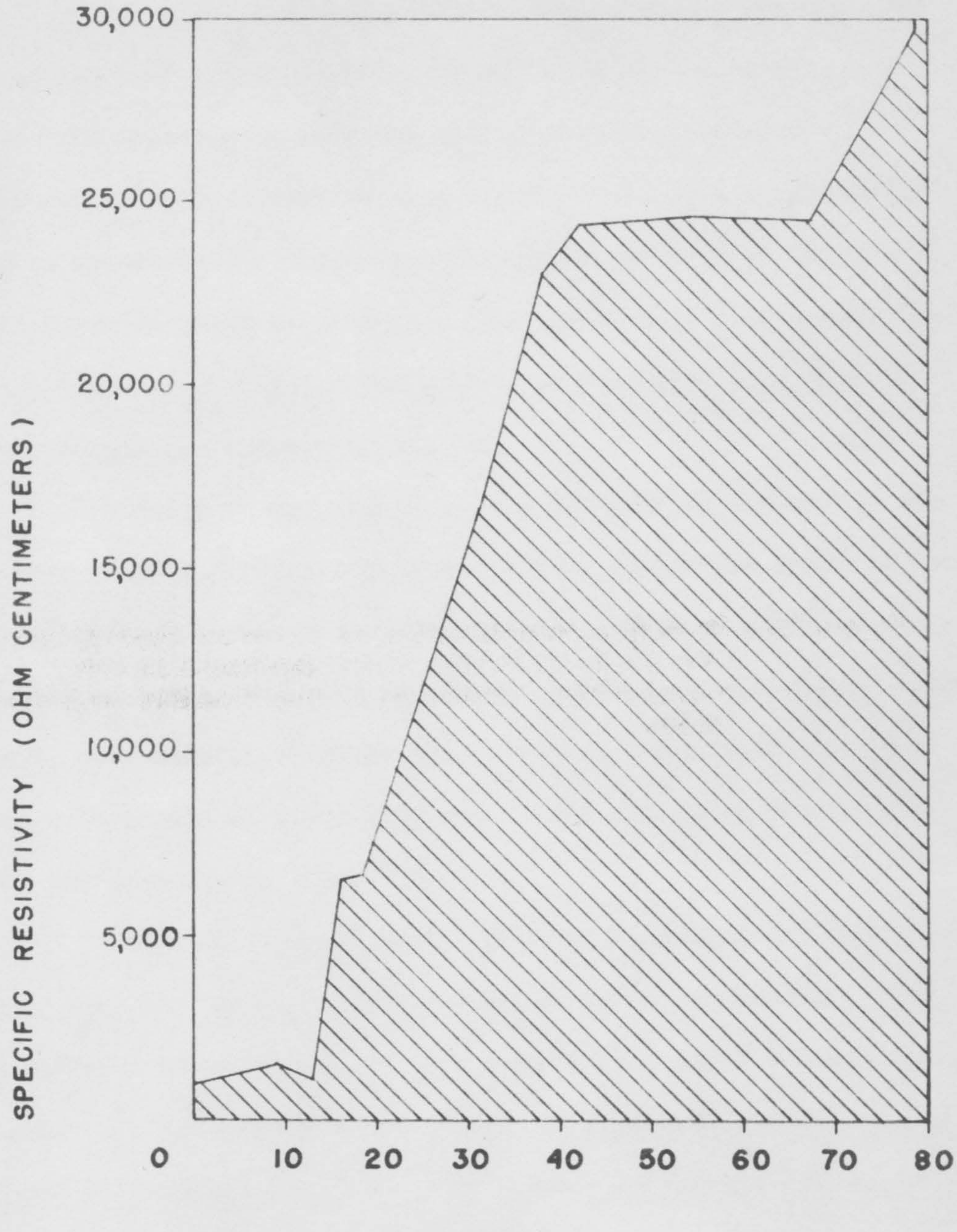
Table 9.--SPECIFIC RESISTIVITIES OF 11 WATER SAMPLES FROM THE CACHE LA POUDRE RIVER EXPRESSED AS OHM CENTIMETERS, CORRECTED TO THE STANDARD TEMPERATURE OF 77°FAHRENHEIT.

Location	Station 1/	Specific resistivity in ohm centimeters at 77°F.	Date sample collected
Windsor	0	691	8/30/57
Timnath	9	1,110	9/5/57
Prospect Bridge	13	700	9/7/57
Linden Bridge	16	6,452	9/5/57
Shield Bridge	18	6,571	9/5/57
Mouth of Canyon	31	16,692	8/23/57
Columbine	38	23,025	8/26/57
Mishawaka	42	24,419	9/3/57
Indian Meadows	54	24,699	8/26/57
Poudre Ponds	67	24,560	9/3/57
Sportsman Lodge	78	29,798	8/26/57

1/ Station corresponds to map-estimated stream mileage with station 0 as the reference point.

It is apparent from Table 9 and Figure 10 that wide variations in specific resistivity can be expected. Over this 78 mile length of river resistivity varied 4,300 per cent. From this it may be understood readily that currents drawn by paddle electrodes will exhibit proportionately wide variation. Although commercially distilled water may have a resistance of 500,000 ohm centimeters, the highest water resistivity recorded during field tests was 75,128 ohm centimeters at 45°F. This resistivity was recorded in the East Inlet to Grand Lake. Alternating voltage with peak to peak voltage of 650 volts ($2 \times \sqrt{2} \times 230$ volts) permitted capture of some

Figure 10.--Specific resistivities of 11 water samples from the Cache la Poudre River expressed as ohm centimeters, corrected to the standard temperature.


30,000
25,000
20,000
15,000
10,000
5,000
SPECIFIC RESISTIVITY (OHM CENTIMETERS)
0
10
20
30
40
50
60
70
80
STREAM DISTANCE (MILES)

fish at this resistivity. Comparable direct current voltage has not been tried in this location.

Table 10 is a summarization of pertinent data recorded during electrofishing experiments utilizing pulsed direct current. These data approximate required pulsed voltages and currents for acceptable electrofishing results under the listed conditions. Where voltage selection was possible, optimum pulsed voltage was determined experimentally by observing fish response. Information presented for the two highest resistivities was secured by the use of high voltage, low current dynamotors.

Average pulsed currents were recorded as accurately as possible over comparable stream bottoms at equivalent water depths and employing a parallel ten foot spread between two paddle electrodes. Currents increased with greater depths and bottom siltation. Hence efforts were made to minimize the extent of these variables by a deliberate choice of recording site. Duty cycles varied from 26 to 41 per cent during these tests.

Table 10 covers a range of water resistivities four times larger than the "normal" range mentioned by Meyer-Waarden (1957). The extremes of water resistivity required the highest volt-ampere relationship for effective shocking. It should be noted that the highest volt-ampere requirement is about 2.46 per cent of the rated wattage capacity of the 2,500 watt direct current generators commonly used in Colorado and Wyoming! These data indicate that an average pulsed voltage of 30 to 40 volts minimum value is required at the

Table 10.—SPECIFIC RESISTIVITIES, STEADY DIRECT CURRENT VOLTAGE, AVERAGED PULSED VOLTAGE AND CURRENT, AND AVERAGE VOLT-AMPERES REQUIRED FOR ACCEPTABLE ELECTROFISHING RESULTS IN SEVEN STREAM LOCATIONS OF NORTHEASTERN COLORADO.

Location	Water temperature at time of electro-fishing in Degrees F.	Specific resistivity at water temperature	Specific resistivity in ohm centimeters at standard temperature	Steady direct current voltage 1/	Average pulsed direct voltage	Average pulsed current in amperes	Average volt-amperes
Cache la Poudre River (Timnath)	70°	1,226	1,110	140	36	1.18	42.48
Michigan River	58°	4,186	3,301	90	30	0.30	9.00
North Platte River	57°	5,314	4,126	110	33	0.32	10.56
Laramie River	50°	8,124	5,717	120	38	0.24	9.12
Cache la Poudre River (Mouth of Canyon)	62°	16,155	13,407	205	79	0.31	24.49
Pennock Creek	56°	38,799	29,754	400	165	0.22	36.30
Cache la Poudre River (Sportsman Lodge)	50°	42,343	29,798	520	205	0.30	61.50

1/ Voltage measured before current interruption.

four lowest resistivities. At the three highest resistivities, increased voltage is necessary to gain a proportionate increase in current density.

It should be noted that these four streams differ in width, average depth, and volume of flow, as well as in terms of specific resistivity. No accurate measurements of these features were made. Undoubtedly these additional three variables are important. For example, an average pulsed voltage of 165 volts was adequate for Pennock Creek, but too low for the Cache la Poudre River. The volume of Pennock Creek was about 8 cubic feet per second, while the flow of the Cache la Poudre River was about 400 cubic feet per second.

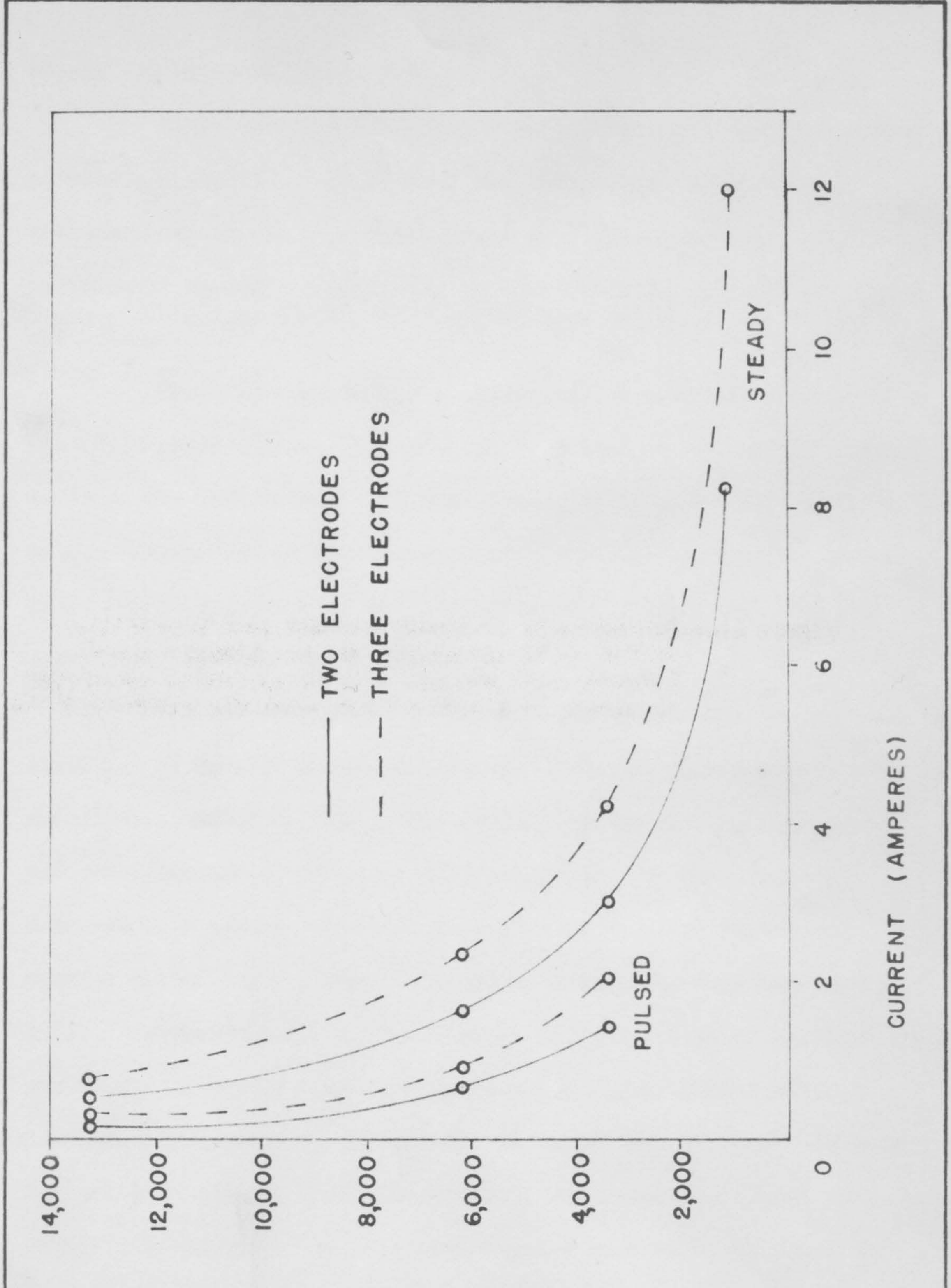
For larger streams such as the Cache la Poudre River, a second catching electrode is advantageous. Table 11 and Figure 11 shows the relationship of currents drawn by three electrodes to currents drawn by two electrodes. Both steady current and pulsed current are graphed, except for the lowest resistivity. Available equipment did not allow current measurement with pulsed voltage at this resistivity. Average pulsed voltage was not recorded during these measurements. These data were recorded October 12, 1957.

Table 11 and Figure 11 indicate that within the specific resistivity range of 1,233 ohm-centimeters to 13,303 ohm-centimeters, corrected to the standard temperature, currents drawn by three electrodes are about one-third greater than currents drawn by two electrodes. This is true whether steady direct current voltage or pulsed voltage is applied to the electrodes. Whether or not this relationship holds true beyond this resistivity range has not been deter-

Table 11.--MEASUREMENTS OF STEADY CURRENT WITH A POTENTIAL OF 225 VOLTS DIRECT CURRENT AND AVERAGE PULSED CURRENTS WITH TWO AND WITH THREE PADDLE ELECTRODES IN STREAM LOCATIONS OF FOUR SPECIFIC RESISTIVITIES.

Location	Water temperature in degrees	Specific resistivity in ohm centimeters at standard temperature	Steady direct current in amperes		Average pulsed current in amperes	
			two electrodes	three electrodes	two electrodes	three electrodes
Cache la Poudre River (Timnath, Colorado)	55°	1,233	8.2	12.0		
North Fork of Cache la Poudre River	57°	3,472	3.0	4.2	1.4	2.0
Cache la Poudre River (Bellvue, Colorado)	53°	6,133	1.6	2.3	.68	.9
Cache la Poudre River (Fort Collins Water Works)	50°	13,303	.56	.77	.22	.3

Figure 11.--Measurements of steady current with a potential of 225 volts direct current and average pulsed currents with two and with three paddle electrodes in stream locations of four specific resistivities.



14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
2
4
6
8
10
12
SPECIFIC RESISTIVITY (OHM CENTIMETERS)
CURRENT (AMPERES)
TWO ELECTRODES
THREE ELECTRODES
PULSED
STEADY

mined, but it seems likely that it does.

Since specific resistivity is such an important phenomenon of water, a limited discussion of the subject may be justified. Because water may be a good insulator or a good conductor, the importance of specific resistivity to electrofishing can not be underestimated.

Specific resistivity of water refers to a measurement of dissolved electrolytes. A conductivity bridge is ordinarily employed to determine this value. The result is usually expressed in terms of ohm centimeters at a certain temperature. If desired, the same value may be expressed as specific conductivity by taking the reciprocal of specific resistivity.

The dissolved solids that normally contribute to the resistivity of natural waters include the carbonates, sulphates, and chlorides of calcium, magnesium, sodium, and potassium, silicic acid, and small amounts of nitrogen and phosphorus. Of less frequent occurrence, compounds of iron, magnesium and varying amounts of organic matter may be present (Ruttner, Transl. by Frey and Fry, 1953). Heavier mineralization results in a reduction of specific resistivity. A lower temperature produces a higher resistivity. McMillan (1928) plotted 15 specific resistivities of different waters against temperatures on semilogarithmic paper and determined that the resistivity curves at various temperatures were straight lines and parallel to one another. Therefore, specific resistivities may be compared to one another at a common reference temperature. Jackson (1955a) presents a table of temperature factors for use in correcting specific resistivities to the standard temperature of 77°F. This table, adapted from L. A. Richards (1947), is included in the appendix.

Seasonal variations in resistivity are common. Ordinarily low stream levels may be associated with lower specific resistivities because of less runoff that is low in electrolytes. Over a four day period 10 and 12 per cent variations in specific resistivities were noted in water samples collected from the Cache la Poudre River. Succinctly, it should be recognized that specific resistivities vary perceptibly from one location to another on the same stream, and probably vary throughout the season for a single location on a stream. Clearly, these variations in specific resistivity will influence voltage and current requirements for effective electrofishing.

German electrofishing equipment.--As mentioned in Chapter II, a German electrofishing apparatus similar to the Salmo-Super described by Meyer-Waarden (1957) was secured from Utah State University. Although reports on this type of equipment were not in uniform agreement relative to its efficiency, German reports and the small bulk of the impulse generator were sufficient reason to test the device under laboratory and field conditions.

Upon arrival, the German impulse generator was known to be defective. Professor John E. Dean, Head of the Electrical Engineering Department, examined it and made necessary repairs. Initially, current drawn by the unit was 35 amperes. After reversing several leads, current was reduced to four amperes, a more reasonable load.

Several badly burned vibrator contacts also had to be changed. Following these repairs, the unit was tried at the Bellvue Hatchery and in several streams. All tests were equally disappointing. Exposed to maximum output in the fish shocking tank, trout were merely stimulated into slight movement, exhibiting a Code 1 response. During one stream test when fish were collected with the unit, three cutthroat trout, Salmo clarkii, were captured in about 200 feet of stream. For comparison, a single small pool in the same area was shocked with 115 volts alternating current and 30 trout of various sizes were recovered.

These experiments suggested that certain unknown defects probably remained. Meyer-Waarden (1951) described a unit similar to the one tested that presumably was effective for electrofishing. Requests of the manufacturer for a parts list and circuit diagram were not acknowledged. Following a change in management of the company, letters of complaint about the equipment were unanswered.1/ Without a circuit diagram, general repair of the unit seemed inadvisable, and it was returned to Utah State University.

It should be noted that the German impulse generator was compactly designed. The 12 volt battery could be slung by straps to the generator, thereby making one load of about 70 pounds. The vibrator seemed to be particularly well constructed and apparently capable of extended use. The generator included a feature that permitted battery recharge from 110 volt alternating current. This would result in a certain economy of operation.

1/ Letter from W. F. Sigler, Utah State University, dated August 13, 1956 to the author.

The electrode system was delicate in comparison to equipment used in Colorado and Wyoming. Wiring was lighter in weight and connections weaker than those ordinarily used in this area. Threaded connections of the collapsible dip net lacked necessary rigidity for moderately strenuous field use. Dip net material resembled plastic, lacked durability, and was more difficult to repair than cotton net.

Although the German impulse generator incorporates four desirable features, viz., battery operation, limited bulk, voltage selection and current pulsation, the range of equipment application is limited. Considering voltage requirements in resistive mountain streams, which probably are at least 520 volts direct current, the equipment is obviously underrated at 250 volts direct current. Meyer-Waarden (1957) mentions a "normal average range" of 1,000 to 10,000 ohm centimeters and the complications involved when working in waters beyond this range. Resistivities from 200 ohm centimeters (Jackson, 1955a) to 75,128 ohm centimeters have been recorded in Colorado. Plainly equipment such as that tested will not accommodate this range of needs. The basic principles are good, if the range of application could be extended. However, past experience has indicated a lack of cooperation on the part of German manufacturers to requests for information. Unless a change of attitude has occurred, difficulties in correspondence might continue to be a handicap to equipment maintenance and further improvement of the German apparatus.

Variable voltage pulsating unit.--Fish collection on streams by the use of alternating current and direct current electrofishing equipment has been discussed. Observations have been made on resistive streams and conductive stream locations and on some intermediate water types. Field experiments have indicated that the galvanotaxic property of direct current may be exploited throughout the range of water resistivities studies. Specific resistivities of streams in northeastern Colorado have varied from 1,226 ohm centimeters to 75,128 ohm centimeters at the time of electrofishing. Currents drawn by two paddle electrodes in natural streams have varied from 12 amperes to 0.12 amperes with 195 to 230 volts direct current. For resistive waters it has been essential to increase the potential across two electrodes to effect higher currents. On the other hand, fish collections can be made with reduced direct current voltages in conductive waters, thereby keeping current output within the limitations of the generating equipment. Evidence accumulated in resistive streams suggests that a potential of 700 volts direct current may be necessary for fish collection work in highly resistive water such as the East Inlet to Grand Lake. A steady potential of 100 volts is perhaps sufficient for conductive waters. Power requirements may be reduced, and anodic reactions of fish improved by current interruption.

Employing the principles confirmed by these field tests, a variable voltage pulsating unit was designed and constructed by Robert D. Rhodus, electrical engineering student at Colorado State

University. A multi-tap transformer permits a selection of alternating current voltages from 100 volts to 700 volts. This voltage may be used directly, or rectified to direct current and interrupted by the pulsating unit described in Chapter II. Current interruption occurs in an oil bath, so as to minimize damage to the commutator surface. Three separate outlets permit a choice of alternating current, direct current or pulsed direct current. An 11-position switch allows a voltage selection within the above range. The potential across the electrodes can be adjusted to requirements dictated by stream conditions such as specific resistivity, number of paddle electrodes employed, and water depth and flow. Transformer fuses and rectifier fuses give maximum protection against short circuits and current overloads. A 115 volt alternating current, 1,000 watt generator is used as the power source for this variable voltage pulsating unit. A circuit diagram and parts list are included in the appendix, and a picture of the completed unit appears on page 84. The weight of the unit is 64 pounds. The electrical components are enclosed in an aluminum case equipped with handles for transport. Approximate overall dimensions of the case are 16 inches by 16 inches by 14 inches in height. This unit should facilitate and improve fish collection work on streams. It will also provide a means by which the extremes of water resistivity may be studied further relative to voltage requirements essential to satisfactory electrofishing.

Figure 12.--Variable voltage pulsating unit.

Electrocution experiments

Attention is directed to the problem of managing fish populations in large reservoirs. The histories of such reservoirs often show that fishing for game species is good for a period of time following impoundment. Later, coarse fish commonly gain predominance, which necessitates chemical treatment of the water to kill all fish. After eradication reservoirs frequently become reinfested with undesirable species. Two familiar sources of recontamination are recognized. First, a well intentioned but uninformed fisherman may empty his minnow bucket when he is through fishing. Secondly, undesirable species in the drainage may immigrate into the reservoir, entering by way of the inlets. Public education programs are necessary to alleviate the first condition. The second source of reinfestation poses a biological and mechanical problem that must be met under difficult field conditions.

Holbrook Reservoir near Swink, Colorado, is an example which in some ways typifies this situation. It is currently providing acceptable fishing, although a coarse fish problem is imminent. This reservoir is filled by the Holbrook Canal, a diversion out of the Arkansas River near Manzanola, Colorado. A lateral out of the main canal extends to the reservoir. This canal is about 12 feet wide and 6 feet deep and reportedly carries water volumes up to 450 cubic feet per second. A gate across the main canal permits its entire flow to be diverted into the reservoir.

Inasmuch as electricity has been used to kill lampreys and

Chinese crabs, an electric barrier was considered for this reservoir lateral. Prior to installation, it seemed mandatory that some of the contingencies of a lethal barrier be investigated under laboratory conditions. Since alternating current seems more injurious to fish, is readily available, and can be transformed, it was selected in preference to direct current. Voltages and current densities were varied individually and the effects on minimum lethal exposure periods for 100 per cent mortality of carp noted. Specific resistivities were determined throughout the experiment to afford an estimate of minimum lethal exposure periods associated with different water resistivities. Except for a few tests performed in the College of Forestry, the experiments were conducted in the College of Engineering at Colorado State University.

The work of Whitney and Pierce (1957) will serve to focus the attention of the reader on certain concepts that are important to the understanding of the following material. These authors studied the resistances of three carp. They determined the electrical resistances in ohm centimeters of a plastic tank of water with and without a live carp. These measurements yielded a resistance ratio of water to carp of 3.0 to 1.0. Specific resistivity of the water, computed from tank dimensions, was 3,560 ohm centimeters. Therefore, the resistivity of the fish was about 1,180 ohm centimeters at 68°F. The carp was killed and refrigerated overnight and its resistivity determined. This value was 1,270 ohm centimeters, a resistance which they felt agreed favorably with the previous measurement, considering the possible experimental errors. They checked the mathematical computations by adding salt to the tank water until the resistivity of the water equalled that of the fish. No difference in overall resistance was detected.

The above authors then ascertained the resistivities of one carp at different temperatures. These values were:

Temperature in degrees Fahrenheit	41	50	59	68	77
Fish resistivity in ohm centimeters	2,690	1,840	1,400	975	508

The resistivity of a third carp was 2,800 ohm centimeters at 41°F. They considered these values to be in good agreement. As a result of these experiments, Whitney and Pierce pointed out that the energy input into a fish could vary by a factor of about five times because of the variation in fish temperatures.

The same authors determined electrical field distortion rates that resulted from the introduction of a carp into the plastic tank. Differences in voltage over certain distances were measured without the fish and with the fish immersed in the water. Where water resistivity was 3,800 ohm centimeters and a ratio of 3.0 existed between water and the fish, voltage differences were about 85 per cent of the values determined before the fish was introduced. Where water resistivity was initially about 19,000 ohm centimeters and a water to fish ratio of 7.5 to 1.0 existed, a value of 41 per cent was determined. This experiment pointed out that the effective voltage over the body of the fish might vary by a factor of two because of the resistivity of the water.

The above authors concluded from their experiments that the input of electrical energy into the body of a fish might vary as much as 10 to 20 times, depending upon the temperature of the fish and the resistance of the medium in which it is immersed. The rate of power input is expressed by the relationship:

$$P = \frac{V^2}{R}$$

Where P is the power in watts, V is the voltage, and R is the resistance of the fish. Resistances of a carp were found to vary about five times over a temperature range of 41° to $77^{\circ}F$. Effective voltage across the body of a carp varied about two times. Hence if other variables were constant, the total variation might amount to 20 times.

Presumably, the carp used by Whitney and Pierce were from water of the same specific resistivity. They considered measured resistances in good agreement. Inasmuch as carp from several sources might conceivably enter a lethal barrier zone, it was decided to electrocute carp from two locations to determine any inherent differences in fish resistivity due to environment. At the outset, carp from the Windsor Reservoir System were divided into two groups, one of which was retained in a stock tank at the site of capture, and the other was transferred to a small pond near Colorado State University. About 40 days elapsed before the latter group was utilized in the electrocution experiments.

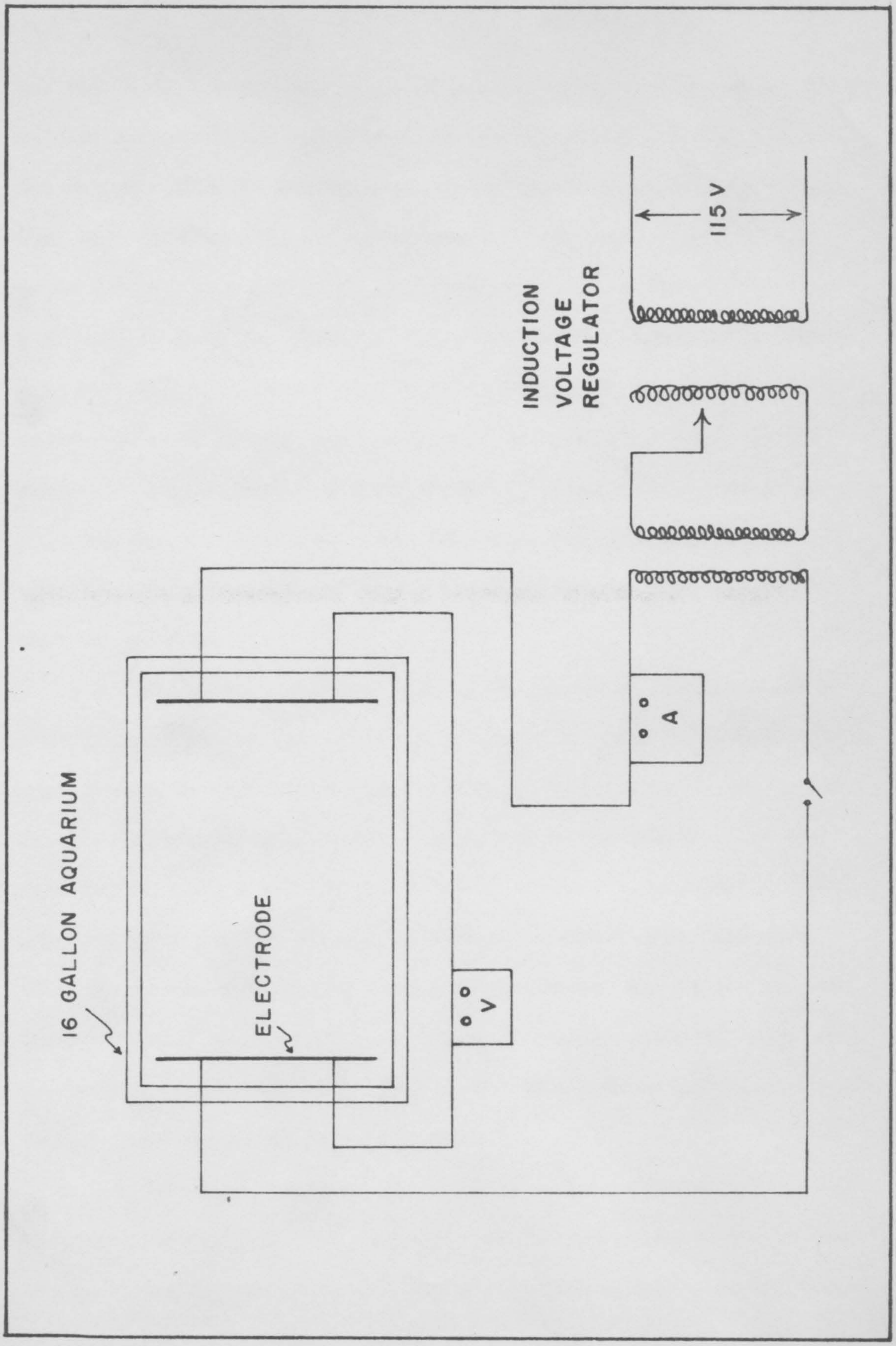
On the assumption that fish temperature cannot be controlled or allowed for in an electric barrier zone, limited control of fish temperature was attempted. This consisted of water temperature measurements of holding facilities and the shocking medium. If a temperature difference of 10°F. existed, water in the holding facilities was permitted to warm to within two to four degrees of the shocking medium. As soon as shocking commenced, this temperature difference was increased again because of the heat dissipated in the water by the electric current.

Sixteen gallon aquaria were used to simulate a lethal electric barrier. Electrodes covering the ends of the aquarium were one-quarter inch mesh hardware cloth. Shocking media included Windsor ditch water and the pond water, in which some of the test specimens had been retained, and tap water. Salt solution was added to the latter to reduce specific resistivity. No control of water temperatures was attempted. However, temperatures of the shocking medium were recorded and they varied from 71° to 85°F. When the latter temperature was reached, tests were discontinued until the shocking medium had cooled to a more favorable temperature. A stop watch was used to time exposure periods.

A heavy duty voltage regulator was used initially to control voltage across the aquarium. With reduced resistivities, it was necessary to employ an induction voltage regulator to handle current loads and maintain voltage levels. Figure 13 shows the electrical arrangement.

Fish and water for holding purposes were brought into the laboratory in small quantities. An aerating system was used initially,

Figure 13.--Circuit employed in the electrocution experiments.


16 GALLON AQUARIUM
ELECTRODE
V
A
INDUCTION
VOLTAGE
REGULATOR
115 V

but was found unnecessary for the limited number of fish held. After voltage intensity was adjusted to the desired level, a group of fish was dropped into the aquarium and timing commenced. Upon immersion, fish were paralyzed almost immediately. Some fecal discharge was noted during the exposures. At termination of the exposure period, a circuit breaker was opened. Carp were removed with a small dip net, marked by fin removal for later recognition, and placed in tap water. Records of each test were maintained and consisted of the number of fish shocked, voltage, current, length of exposure, fins clipped, and the mortality. The technique employed was to approximate the minimum lethal exposure period, narrowing time limits as much as possible.

During the recovery period, shocked fish were observed frequently in order to note signs of recuperation from paralysis. In some specimens, weak gill action was noted after a few minutes, but respiration eventually stopped. Some carp never respired, having died during the exposure or immediately afterward, presumably from respiratory paralysis and heart failure. Where a fish recovered from the shock, gill action became progressively stronger. As control returned, the fish swam weakly on its side, gradually regaining its normal swimming ability. Survivors were shocked repeatedly until 100 per cent mortality was achieved.

Table 12 indicates the effects of four voltage intensities on induced mortality. Volt-amperes are included also, since an increase in voltage brings about a proportionate increase in current.

Water temperatures probably are responsible for slight discrepancies in this relationship. Windsor ditch water, with a specific resistivity of 600 ohm centimeters, was used as the shocking medium. Carp originated in the Windsor Irrigation System.

Table 12.--APPROXIMATE MINIMUM LETHAL EXPOSURE PERIODS AT FOUR VOLTAGE LEVELS FOR CARP FROM THE WINDSOR DITCH SHOCKED IN WINDSOR DITCH WATER.

Voltage	Minimum lethal exposure period in seconds	Number of trials	Number of fish employed	Volt-amperes
115	270	6	9	170
210	100	6	18	626
330	11	6	6	1,749
450	14	17	17	2,970

None of these voltage intensities produced 100 per cent mortality in 10 seconds. At least 330 volts is necessary for 100 per cent mortality in the approximate specified time limit.

Beginning with tap water of 7,632 ohm centimeters specific resistivity, a series of time trials was conducted wherein current densities were increased by the addition of salt solution, while the potential across the electrodes was maintained at 450 volts. Initially, water depth was 7.5 inches and at the termination of the experiment it was 4.8 inches. Over a period of use, current drawn by the shocking medium increased. As water resistivity was decreased, the current, and hence the temperature, increased. As a result of the increase in temperature and current load, sometimes the voltage dropped during an exposure. If the shocking period was sufficiently long, an adjustment in voltage was made. Where adjustments were not made, voltage drops were not more than three per cent. Experimental evidence was not sufficient to indicate mortality effected by an increase in temperature.

Carp directly from the Windsor ditch and carp from the pond near Colorado State University were employed in these current density tests. It should be noted that specific resistivities of water from which these groups of carp were markedly different. Windsor ditch water ranged in resistivity from 553 to 645 ohm centimeters; pond water had an initial resistivity of 5,725 ohm centimeters and at the termination of the tests the resistivity had dropped to 4,674 ohm centimeters. Hereafter, carp from the Windsor ditch are referred to as Windsor ditch fish and those from the pond are considered as pond fish.

Tables 13 and 14 suggest a variation in approximate minimum lethal exposure period that probably can be ascribed to the respective environments from which test carp were taken. Minor differences in approximate minimum lethal exposure periods are indicated at the highest specific resistivities. For the three lowest resistivities, pond carp were four to six times more resistant to electric shock than Windsor ditch carp. Differences between approximate minimum lethal exposure periods for pond carp at specific resistivities of 559 and 266 ohm centimeters was due to two specimens that survived 45 second shocks but perished after 60 second exposure

Table 13.--APPROXIMATE MINIMUM LETHAL EXPOSURE PERIODS FOR CARP FROM WINDSOR DITCH AT FIVE SPECIFIC RESISTIVITIES WITH 450 VOLTS ALTERNATING CURRENT APPLIED TO THE ELECTRODES.

Water resistivity in ohm centimeters	Minimum lethal exposure period in seconds	Number of trials	Number of fish employed	Current in amperes recorded during exposure periods
6,081	375	36	138	.52
1,463	40	22	106	2.05
872	15	38	129	3.40
682	10	11	22	4.20
266	10	12	19	5.65

Table 14.--APPROXIMATE MINIMUM LETHAL EXPOSURE PERIODS FOR CARP FROM POND AT FOUR SPECIFIC RESISTIVITIES WITH 450 VOLTS ALTERNATING CURRENT APPLIED TO THE ELECTRODES.

Water resistivity in ohm centimeters	Minimum lethal exposure period in seconds	Number of trials	Number of fish employed	Current in amperes recorded during exposure period
4,392	360	29	74	.63
872	90	37	95	3.42
559	40	37	105	3.82
266	60	49	98	5.50

periods. Temperature range of the shocking medium at the time of approximate minimum lethal exposures was 76° to 82°F.

A single experiment was made to determine time required for a conditioning response to a new medium. Five shocked fish and five unshocked fish from the group of pond carp were placed in Windsor ditch water overnight. About 24 hours later these 10 carp and 10 more that had been held in resistive pond water were shocked in groups of four. To minimize differences in current densities, two carp were taken from each holding receptacle for each test. Of ten fish held overnight in conductive ditch water, seven survived. Of 10 fish held in resistive pond water, four survived the experiment. Two of the survivors were kept a second night in ditch water, after which one perished following a 60 second exposure. The other survived a 75 second exposure, but died after a 90 second exposure. Six times more energy was required to kill this carp than was necessary to kill the most resistant of Windsor ditch carp under comparable conditions. This test suggested that changes in fish resistivity are subtle and probably require more than 36 to 48 hours. Furthermore, individual variations in resistance to electric current probably should be considered.

Table 15 affords evidence of the individual variability in induced mortality observed during the experiments. In this sequence of trials, one particular fish survived four individual exposures to be killed eventually after a shock of 40 seconds duration. About twice the energy necessary to kill other fish in this series was required to electrocute this fish. Thus it appears that individual fish may be particularly resistant to electric shock.

Table 15.--WINDSOR DITCH CARP SHOCKED IN WATER OF 1,463 OHM CENTIMETERS SPECIFIC RESISTIVITY WITH 450 VOLTS ALTERNATING CURRENT.[1]

Number of trials	Exposure period in seconds	Number of fish employed	Number dead	Number alive
2	5	10	8	2
5	10	25	24	1
8	15	40	38	2
2	20	10	9	1
1	25	5	5	0
2	30	10	9	1
1	40	1	1	0
1	45	5	5	0

1/ Current 1.92 to 2.05 amperes.

Measurements of 116 carp electrocuted during these time trials averaged 2.39 inches in total length. Range was 1.2 inches and the standard deviation was 0.364. Coefficient of variation for the group measured was 11.04 per cent.

In view of the small size of the above carp, it was fitting to shock carp of various sizes to determine whether or not larger carp succumb at the same exposures. This work was done about January 1, 1958. Specific resistivity of the shocking medium was 658 ohm centimeters. Carp and water were secured from the Timnath ditch near Timnath Reservoir. This site is about two miles northeast of Timnath, Colorado. Carp and water were allowed to warm to 67°F. before electrocution experiments were commenced. Twenty-eight time trials were conducted. Size range of carp shocked was from 2.5 to 10.0 inches. No difference in approximate minimum lethal exposure periods within this size range could be detected. Exposures of 30 seconds duration were necessary for 100 per cent mortality of this group. Comparison of this exposure period with Table 13 indicates that three times the energy level was necessary for 100 per cent mortality of carp in this instance. Specific resistivities of Windsor ditch and Timnath ditch waters were of similar magnitude.

To summarize the electrocution experiments, an increase in either voltage or current reduced the length of exposure for 100 per cent mortality of carp under the conditions of the experiment. However, groups of carp from two different locations did not yield uniform results relative to required approximate minimum lethal exposure periods. Carp from the resistive habitat of the pond were four to six times more resistant to electric shock at three reduced resistivities than were the carp from the less resistive habitat of Windsor ditch. Whether or not acclimation of the former group to a new habitat was complete at the termination of a 40 day period is unknown. Conditioning periods of 36 to 48 hours were ineffective in demonstrating acclimation.

The lack of uniformity of minimum lethal exposure periods within the group of Windsor ditch carp indicates that differences in supposedly homogeneous groups of carp can be expected. This indicates that there may be a differential in the extent to which salts are concentrated in the bodies of individual fish from the same habitat. Fish temperature should not have been a factor since carp in this group were held under identical conditions of water temperature and specific resistivity.

Because fish are cold-blooded animals, their body temperature approximates that of the water in which they are immersed. That carp from Timnath ditch taken in mid-winter required three times more energy for 100 per cent mortality than a group of carp from Windsor ditch collected during the spring suggests a seasonal variation. Presumably, this variation may have been due to body temperature variations or due to differences associated with metabolic activity which is reduced during the winter.

These data indicate that particularly resistant carp might pass downstream through a lethal electric barrier zone unharmed, to repopulate a recently rehabilitated reservoir. Therefore, because of the variables mentioned, it appears infeasible to consider further a downstream lethal electric barrier against carp immigration. Relative to differences between species, McLain (unpublished) determined that more than twice the energy required to kill bluegill sunfish, *Lepomis macrochirus*, was not sufficient to cause 100 per cent mortality of green sunfish, *Lepomis cyanellus*. The latter species is one of several other undesirable fish species in this region.

Chapter IV

DISCUSSION

Electrofishing is one of the more modern techniques employed in the mass capture of fish from streams. In the past, principally alternating current and direct current have been used in Colorado for this purpose. Alternating current has been employed in the resistant streams characteristic of granitic mountainous areas and direct current has been used in the moderately hard waters associated with the plains and foothill country. This has necessitated two generating units. Because of the added physiological stimulation and power economy, pulsed currents have been recently investigated for electrofishing.

To the end that fish sampling efficiency could be improved with pulsed current, a direct current interruptor was constructed. Considering the means by which direct current may be broken, a mechanical device was selected. This device is described in Chapter II (Figure 2). The current conducting period was set at 35 per cent. The pulse shape was an abruptly peaked rectangular voltage wave.

Controlled shocking experiments with rainbow and brown trout as test animals were performed to determine the optimum pulse repetition rate. The objective of these experiments was to determine the repetition rate that was effective in eliciting anodic attraction with the least energy requirement. By utilizing such a repetition rate in stream electrofishing operations, it was believed that effective electrical fields in the water would be enlarged proportionately, thereby enhancing success. Within the range of pulse repetition rates from 76.6 pulses per second to 124.8 pulses per second, volt-ampere requirements for optimum trout response were very similar. A repetition rate of 95.2 pulses per second was selected for use during field tests.

Because the extremes of water resistivity, i.e., resistive and conductive streams, have presented the greatest problems to satisfactory electrofishing, examples of such locations were selected for study. Evidence was gathered within the range of water resistivities studied that pulsed currents increased electrofishing success. The advantages of pulsed currents were most conspicuous within the typically limited range where direct current of 230 volts is commonly used. In more resistive waters it was necessary to increase direct current voltage. With 240 volts alternating current as a standard of comparison, it was essential to increase steady direct current potential to 520 volts for the resistive waters studied. Average direct current pulsed voltage of 205 volts was superior to 240 volts alternating current for fish collection work in the resistive water of the Cache la Poudre River near Sportsman Lodge. On the same stream near Timnath, Colorado, steady direct current voltage and pulsed direct current voltages required for successful electrofishing in conductive water were determined by observation of fish responses with various voltages applied to the electrodes. The average pulsed volt-ampere requirement for acceptable results within the Timnath area was 12 per cent of the steady direct current requirement. The largest pulsed current power demand requisite to effective shocking were noted at the above extremes of water resistivity. Within the specific resistivity range of 4,186 ohm centimeters to 8,124 ohm centimeters, electrical energy requirements were less than one per cent of the wattage capacity of a 2,500 watt direct current generator. The largest power consumption with pulsed direct current was 2.46 per cent of this generator capacity.

Field tests provided an indication that pulsed voltage, because of its added physiological stimulation, must be carefully selected for application to the electrodes so as to avoid excessive mortality of fish. Whereas steady direct current may be employed over a fairly wide range of resistivities without danger to fish, pulsed direct current voltage must be selected with greater caution. Fish mortality during the Pennock Creek studies with an average pulsed voltage of 165 volts was 4.7 per cent. This mortality could have been reduced by means of voltage control. By the close examination of the collected fish it should be possible to avoid any excessive fish mortality. It appears that a certain mortality is almost inevitable when making collections of fish with electricity.

In keeping with the overall objective of the project, a German electrofishing apparatus was secured to evaluate its utility for the purpose in Colorado. This unit was described in Chapters II and III. Because of defective operation this unit probably was not representative of similar units. However, the maximum voltage output of 250 volts approached that of a similar unit described by Meyer-

Waarden (1957). This author states that the maximum potential of the Salmo-Super is approximately 270 volts. Such a voltage is inadequate for resistive waters. Despite the advantages of voltage selection, battery operation, limited bulk, and current pulsation, the equipment is not recommended for use in Colorado and Wyoming.

Based upon the needs determined during controlled fish shocking experiments and field tests, a variable voltage pulsating unit was constructed (Figure 12). An 11-position switch permits a selection of voltage intensity from 100 to 700 volts. This potential is available as direct current, alternating current, or as pulsed direct current. A selection of 11 voltage intensities over the above range represents an improvement over the unregulated generator equipment previously used in Colorado and Wyoming. In addition, the feature of current interruption provides for reduced power demands. Examination of the data presented here indicate that pulsed direct current may be employed to advantage in electrofishing throughout the range of water resistivities studied. The only apparent disadvantage to the use of pulsed voltage for electrofishing is the need for caution relative to electric field intensity, so as to avoid excessive fish mortality. Sufficient voltage control should reduce fish mortality to an acceptable minimum.

Electrocution experiments

Electrical barriers have been employed to kill sea lampreys and Chinese crabs. Inasmuch as such barriers have produced satisfactory success in controlling undesirable species, a lethal barrier was considered for use on a diversion ditch into Holbrook Reservoir near Swink, Colorado. Such a barrier would have to be almost instantly effective in producing 100 per cent mortality. Unless the barrier were immediately effective in producing mortality, fish, although paralyzed, might be carried by water flow into the reservoir. If the shock were not sufficiently intense, recovery might result and another undesirable fish population started in the reservoir.

The carp is one of the most undesirable fish species in Colorado. It is a prolific species and capable of severe habitat destruction. Because it is particularly objectionable, means are sought whereby carp can be kept out of reservoirs and lakes. In view of the possibilities of an electric barrier, electrocution experiments were conducted to determine the individual effects of different alternating current voltages and current densities. A 16-gallon aquarium equipped with one-quarter inch mesh hardware cloth was used to simulate an electric barrier zone. Carp were used as test animals and dropped into the aquarium without regard to orientation in the electric field. The technique employed was to approximate the minimum lethal exposure period, narrowing time limits as much as possible. As a criterion of feasibility, 100 per cent mortality must occur in ten seconds or less.

It was recognized at the outset that currents drawn by the electrodes would be greater at reduced resistivities. Therefore it was desirable to shock a group of carp at different water resistivities to determine necessary exposure periods. Also, in view of the range of water resistivities encountered near the

Colorado State University Campus, it was deemed advisable to shock two groups of carp from different habitats to determine inherent variations that might be a result of environmental differences. The available supply of carp was divided into two groups, one of which was retained at the site, and the other was transferred to a small pond near the Colorado State University Campus. About 40 days elapsed before the latter group was utilized in the electrocution experiments.

The influence of four voltage intensities on induced mortality was studied. None of the voltages applied to the aquarium electrodes was effective in producing 100 per cent mortality in 10 seconds or less. In order to approach this time period, at least 330 volts was necessary. These tests were run with carp taken from the Windsor Reservoir System.

Carp directly from the conductive water of Windsor ditch were exposed to five different current densities with a potential of 450 volts across the electrodes. Approximate minimum lethal exposure periods were reduced from 375 seconds to 10 seconds by increases in current density. For comparison, carp from the resistive water of the pond were exposed to three similar current densities with 450 volts potential applied to the electrodes. This group was four to six times as resistant to shock as the former group. Specific resistivities of the Windsor ditch varied from 553 to 645 ohm centimeters. Pond water had an initial resistivity of 5,725 ohm centimeters and at the termination of the experiment, the resistivity had dropped to 4,674 ohm centimeters. These studies were conducted during the spring of 1957.

During the above experiments, individual carp were noted to be particularly resistant to shock. For example, one carp from the Windsor ditch survived four individual exposures and was eventually electrocuted upon an exposure of 40 seconds. In the same series of trials, an exposure of 15 seconds killed 95 per cent of the carp employed. Over twice the energy was required to kill this one carp mentioned above.

The mean total length of these carp was 2.39 inches. Because of their small size, a group of fish ranging in total length from 2.5 inches to 10.0 inches was electrocuted to ascertain any difference due to size. These studies were done about January 1, 1958. Under the conditions of the experiment, no difference attributable to size could be detected, i.e., small fish and large fish succumbed with equivalent exposure periods. A difference was noted in the approximate minimum lethal exposure periods, in respect to carp from similar water exposed under similar conditions of voltage and current during the spring electrocution experiments.

Fish temperature and fish resistivity are recognized variables from a standpoint of energy input into a fish. The results of experiments indicate that one or both of these variables are not of uniform magnitude. The individual carp found to be particularly resistant to electric shock were held and shocked under identical conditions of temperature. This seems to rule out temperature as a factor that might account for differences in susceptibility to electric shock in these experiments. Hence it seems reasonable that fish resistivity may vary more widely than expected between waters of different resistivity. Moreover, these variations seem to exist in a single, otherwise homogeneous population.

Suggestions for further study

Electrofishing experiments.--Additional experiments should be performed regarding the extremes of water resistivities encountered in northeastern Colorado. In view of the change of duty cycle during experiments in conductive water, studies should be conducted with the variable voltage pulsating unit to determine whether voltage and current relationships are satisfactory for fish collection work. Indicated alterations can be applied to subsequent variable voltage pulsating units. If current limitations of the variable voltage pulsating unit are exceeded in hard, conductive stream locations, consideration should be given to the utilization of a direct current generator with a rheostat large enough to restrict voltage output to the current limitations of the generator.

High voltage direct current and equivalent pulsed direct current produced by the variable voltage pulsating unit should be tested in the East Inlet to Grand Lake during the sucker spawning season for comparison with previous years' experience. Such a test should produce clear-cut evidence of the adequacy of the high voltage direct current for resistive locations. Moreover, the application of steady direct current voltage and pulsed voltage should produce concrete evidence of the merits of the two types of voltages for resistant streams.

It has been suggested that greater caution is necessary in the selection of pulsed voltage than in the application of steady voltage. If pulsed voltage can be used throughout the range of resistivities determined during the present study, transformer size and weight can be reduced. On the basis of trends established in this work, lesser pulsed voltages should be sufficient for optimum fish collection work. Should finer voltage control prove necessary to alleviate fish mortality, a variac may be inserted in the primary of the transformer, thereby allowing a continuous selection of voltage intensity from zero output to 700 volts.

Because half-wave rectified alternating current would eliminate the pulsating unit, field tests should be performed with this type of power. Should half-wave rectified alternating current prove of equivalent efficiency in fish collection work to pulsed direct current of 95 pulses per second, the bulk, weight, and expense of the variable voltage pulsating unit can be reduced. The maintenance problem of current interruption in an oil bath, and periodic replacement, will be eliminated.

Since a motor-driven interruptor would no longer be necessary, power economy and simplicity would be achieved. In view of the low power requirements and the voltage relationships reported here for successful electrofishing, continuing efforts should be made to bring the variable voltage pulsating unit up to date with the latest developments in the Electrical Engineering field. Moreover, stream electrofishing equipment should be designed for mobility and facility of use. Generator size should be reduced; electrodes and cable should be selected on the basis of light weight and tensile strength, with due regard to the safety of operators. The information presented here should serve as a point of reference for future work.

Research should be performed on various types of electrodes for large pools that might have application to reservoirs and lakes. Since electricity offers the possibility of instantaneous fish samples, it has a definite advantage over gill nets. The feasibility of the trouser leg electrode arrangement described by Joseph (1956) should be studied. Another possibility that seems to have merit is the principle of timed control of electric discharges, where successive portions of an electric seine are energized. Theoretically, this would permit electrodes of larger size, and, because of current pulsation and sequential fields between electrodes, power consumption would not be prohibitive.

Field records of electrofishing experiments should be maintained. These should consist of voltages and currents utilized for a given stream on certain dates. These data together with specific resistivity measurements should provide a pattern that would serve as a guide to future operations. With experience an operator should be able to approximate required voltage for a given stream location on the basis of a specific resistivity measurement.

Experiments in resistive streams have indicated clearly the need for higher voltage. By effecting an increase in voltage, the current through the water is increased so that fish can be immobilized. Recognizing this need for greater voltage, it is essential that the utmost human precautions be taken against injurious or fatal electric shocks. It is unnecessary to point out the inherent danger of electricity. However, since voltage proposed for use in highly resistive water is over three times greater than that customarily used for domestic purposes, danger is probably proportionately greater. Also, pulsed currents increase the human hazard. It is, therefore, imperative that all personnel associated with an operation be cautioned on the dangers involved and means of averting tragedy. Electrode handles equipped with pressure release switches might be a means of preventing dangerous shocks during stream operations. For further discussion of precautionary measures, the reader is referred to administrative reports by Giguere (1954, 1956). In addition, where one hand is sufficient for the job, keep the other hand behind the back or in the pocket when working with electrical apparatus. This is a practice followed and recommended by electrical engineers.

Electrocution experiments.--The variations in resistance of carp noted during the electrocution experiments are a serious obstacle to the development of a satisfactory lethal electric downstream barrier. In view of these variations, continued effort in this direction is not recommended, unless a different approach is taken.

Chapter V

SUMMARY

1. A mechanical pulsating unit for direct current was developed and perfected in the Electrical Engineering laboratory. Utilizing a duty cycle of 35 per cent, rainbow trout and brown trout were exposed under controlled conditions to various voltage levels and pulse repetition rates. The range of pulse repetition rates from 76.6 pulses per second to 124.8 pulses per second produced optimum galvanotaxic response with minimum quantities of power. Power requirements for optimum trout response at a pulse repetition rate of 95.2 pulses per second were 6.7 per cent of steady direct current requirements.

2. Quantitative evidence of electrofishing success under field conditions with direct current, alternating current, and pulsed direct current was compared. The galvanotaxic phenomenon of direct current may be exploited throughout the range of water resistivities studied. Employing pulsed current, an average pulsed voltage of 205 volts was required in resistive water of 42,343 ohm centimeters at 50°F. Satisfactory electrofishing results were achieved with an average pulsed voltage of 36 volts in conductive water of 1,226 ohm centimeters at 70°F. Within this range of specific resistivities, power requirements for acceptable electrofishing results in seven

stream situations ranged from 9.00 to 61.50 volt amperes. The variation in power requirements was from less than one per cent to a maximum of 2.46 per cent of the wattage capacity of the 2,500 watt direct current generators commonly employed for electrofishing.

3. The additional physiological stimulation of pulsed current necessitated voltage control so as to avoid excessive fish mortality. Apparently, a pulsed current density of about 0.2 to 0.3 amperes was necessary for satisfactory electrofishing results with the paddle electrodes employed. Some divergence was noted in this requirement that seemed to be associated with water flow and fish species collected.

4. A variable voltage pulsating unit that incorporates some of the needs indicated by field research was constructed. A multi-tap transformer and full-wave rectification circuit allows a choice of alternating current or direct current. The direct current voltage may be interrupted by means of the pulsating unit, achieving power economy and the added physiological stimulation of pulsed current.

5. Electrocution experiments were performed to ascertain the approximate minimum lethal exposure periods of carp to electric fields of several conditions of alternating current voltage and current density. An increase in voltage from 115 to 330 volts reduced necessary exposure periods from 270 seconds to 11 seconds. Groups of carp from two different habitats were exposed to electric fields of similar current density. At three current densities,

four to six times more energy was required for 100 per cent mortality of the carp from the more resistive habitat. Some individual carp were noted to be particularly resistant to electric shock.

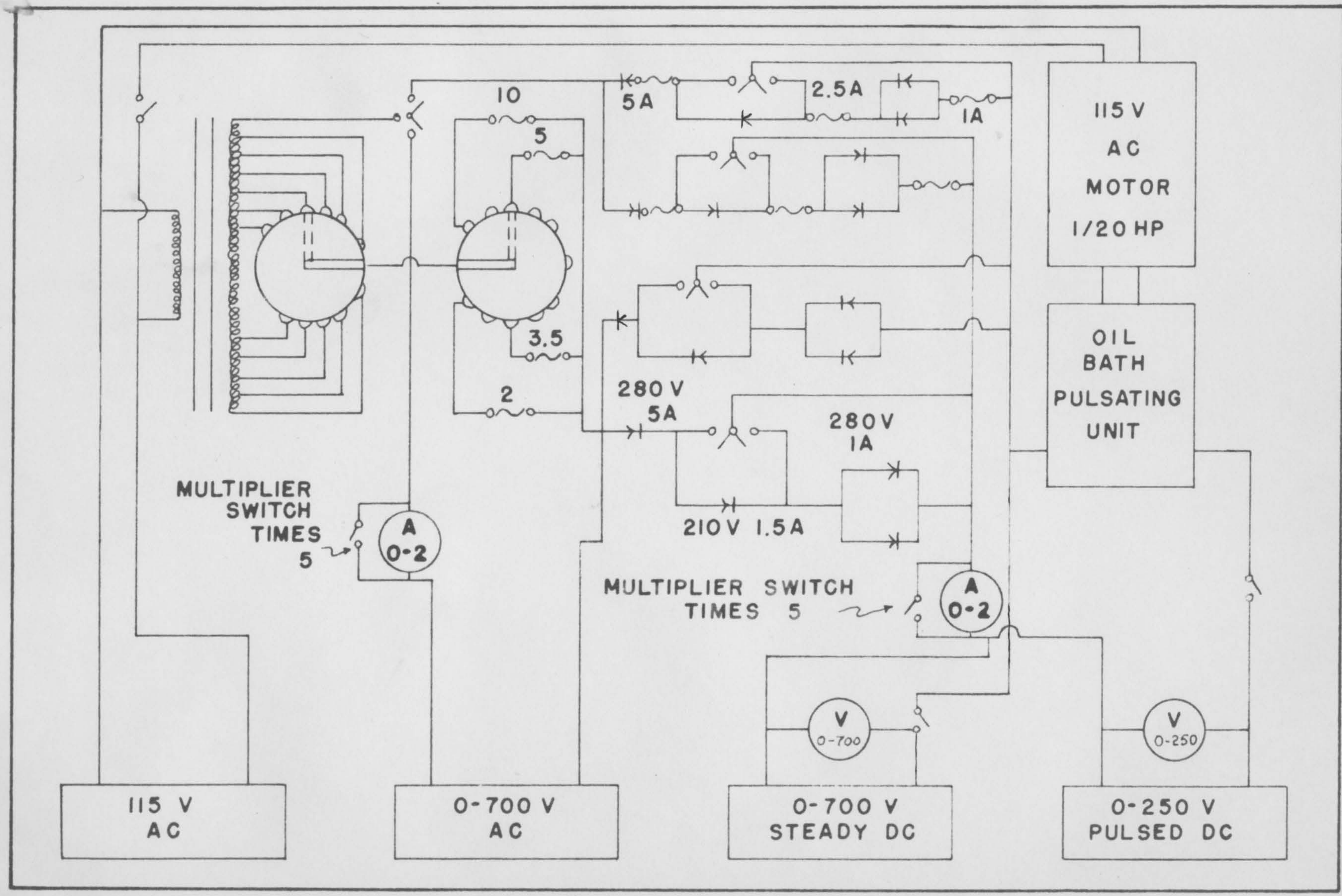
A P P E N D I X

APPENDIX A

VARIABLE VOLTAGE PULSATING UNIT
(Parts List)

Pulsating Unit		$ 11.25
1 - AC motor (1/20 H.P., 1,550 R.P.M.)		8.99
Rectifiers		
4 - 40 LF.	@ $6.08 . . .	24.32
4 - 30 LF.	@ 4.35 . . .	17.40
8 - M-500.	@ 1.95 . . .	15.60
16 - Holders.	@ .10 . . .	1.60
Transformer		55.00
2 Ohmite Switches.	@ 3.00 . . .	6.00
5 - S. P. S. T. toggle switches	@ .52 . . .	2.60
5 - Three position switches. . .	@ .69 . . .	3.45
1 - return switch.	@ .96 . . .	.96
10 - fuse posts	@ .25 . . .	2.50
Meters		
1 - 0-2 DC ammeter		9.00
1 - 0-2 AC ammeter		8.50
1 - 0-250 DC voltmeter		10.26
1 - 0-750 DC voltmeter		10.00
Aluminum case		13.58
Recepticals, 4		3.20
Miscellaneous wire, fuses, etc.		5.00
		$209.21

APPENDIX B


115 V
AC
MOTOR
1/20 HP
OIL
BATH
PULSATING
UNIT
10
5
3.5
2
5A
2.5A
1A
280 V
5A
280V
1A
210V 1.5A
MULTIPLIER
SWITCH
TIMES
5
A
0-2
MULTIPLIER SWITCH
TIMES 5
A
0-2
V
0-700
V
0-250
115 V
AC
0-700 V
AC
0-700 V
STEADY DC
0-250 V
PULSED DC

APPENDIX C

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
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

* 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.

LITERATURE CITED

LITERATURE CITED

Applegate, Vernon C., Bernard R. Smith, and Willis L. Nielsen.
1952 Use of electricity in the control of sea lampreys: electromechanical weirs and traps and electrical barriers. U. S. Fish and Wildlife Service, Special Scientific Report: Fisheries No. 92, 52 p.

Chute, Walter H., et al.
1948 A list of common and scientific names of the better known fishes of the United States and Canada. American Fisheries Society, Special Publication No. 1, 45 p.

Guigere, Paul E.
1954 Development and use of electro-fishing apparatus in Region V. California Dept. of Fish and Game, Administrative Report 54-17, 34 p.

——— 1956 Modifications of a D.C. electro-fishing apparatus. California Dept. of Fish and Game, Inland Fisheries Administrative Report No. 56-4, 10 p.

Haskell, David C.
1954 Electrical fields as applied to the operation of electric fish shockers. New York Fish and Game Journal, 1(2): 130-170.

Haskell, David C., and W. J. Adelman, Jr.
1955 Effects of rapid direct current pulsations on fish. New York Fish and Game Journal, 2(1):95-105.

Jackson, Frederick W.
1955a Electrofishing as applied to Colorado waters. M. S. Thesis, Colorado A and M College, Fort Collins, 127 p.

——— 1955b Progress report on the development of a lethal electric fish barrier. Colorado Cooperative Fisheries Research Unit, Quarterly Report, 1(3,4):12-16.

——— 1956 A general description of the electrofishing equipment of the Wyoming Game and Fish Department. (Typewritten report submitted to the Wyoming Game and Fish Commission, Cheyenne, 6 p.)

LITERATURE CITED -- Continued

Joseph, David C.
1956 New techniques in ocean electro-fishing are developed. Outdoor California, 17(9):13.

Loukashkin, Anatole S., and Norman Grant.
1954 Further studies of the behavior of the Pacific sardine (Sardinops caerulea) in an electrical field. California Academy of Sciences, Proceedings, Fourth Series, 28(6):323-337.

McLain, Alberton L.
1957(?) Electrical energy required to kill small fish. (Typewritten report of the Great Lakes Fishery Investigation, 15 p.)

McLain, Alberton L., and Willis L. Nielsen.
1953 Directing the movement of fish with electricity. U. S. Fish and Wildlife Service, Special Scientific Report: Fisheries No. 93, 24 p.

McMillan, F. O.
1928 Electric fish screen. U. S. Bureau of Fisheries, Bulletin, 44:97-128.

Meyer, P. F.
1951 Ein neuartiges Impulsgerat fur die Elektrofischerei. Translation. Der Fischwirt, No. 3, 6 p.

Meyer-Waarden, P. F.
1957 Electrical fishing. F.A.O., Rome, Fisheries Study No. 7, 77 p.

Ruttner, Franz.
1953 Fundamentals of limnology. Translated by D. G. Frey and F. E. J. Fry. University of Toronto Press, Toronto. 242 p.

Snedecor, George W.
1948 Statistical methods applied to experiments in agriculture and biology. Fourth edition, Iowa State College Press, Ames. 485 p.

Taylor, Glen N.
1955 Galvanotaxic response of fish to pulsating direct current. M. S. thesis, Utah State Agricultural College, Logan. 53 p.

LITERATURE CITED -- Continued

Walch, Albert
1949 Die Einwirkung des elektrischen Stromes auf den Fisch bei der Elektrofischerei. Translation. Allgemeine Fischerei Zeitung, 74(12):213-216.

Whitney, Lester V., and Richard L. Pierce
1957 Factors controlling the input of electrical energy into a fish (Cyprinus carpio L.) in an electrical field. Reprint. Limnology and Oceanography, 2(2):55-61.