GEORGIA INSTITUTE OF TECHNOLOGY

Engineering Experiment Station

PROJECT INITIATION

Date: 10/22/71

Project Title: A Study of the Effects of Electric Currents on Fish*

Project No.: B-400

Project Director: Dr. H. A. Ecker

Sponsor: Georgia Game & Fish Commission; Atlanta, Georgia

Effective September 1, 1971 Estimated to run until: June 30, 1972

Type Agreement: Contract dated September 1, 1971 Amount: $ 5,001.00

Reports Required: Quarterly Progress Reports; Final Report.

Contact Persons: Administrative Matters
Mr. Leon Kirkland
Georgia Game & Fish Commission
270 Washington Street, S. W.
Atlanta, Georgia 30334
Phone: 656-3524

Technical Matters
Mr. Don Johnson
Fisheries Biologist
Georgia Game & Fish Commission
Gainesville, Georgia

*This project will be funded at a total estimated cost of $9,530 with $1,999 provided by the Sport Fishing Institute (B-397), $5,001 by Game & Fish Commission (B-400), and $2,530 by Georgia Institute of Technology (E-200-301).

Assigned to Electronics (Radar) Division

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RA-62(12-66)

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station

M-60 28

PROJECT TERMINATION

Date 5/2/73

PROJECT TITLE: A Study of the Effects of Electric Currents on Fish

PROJECT NO: B-400

PROJECT DIRECTOR: Dr. H. A. Ecker

SPONSOR: Georgia Game & Fish Commission; Atalnta, Georgia

TERMINATION EFFECTIVE: 5/2/73 (Final Report submitted)

CHARGES SHOULD CLEAR ACCOUNTING BY: N/A - All funds expended

Contract Closeout Itmes Remaining: None

RADAR DIVISION

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Form EES 402 (R10-62)

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station

PROJECT INITIATION

Date: 8/26/71

Project Title: A Study of the Effects of Electric Currents on Fish*

Project No.: B-397

Project Director: Dr. J. L. Edwards

Sponsor: Sport Fishing Institute; Washington, D. C.

Effective . . . . . July 1, 1971 . . . . Estimated to run until: . . . . . June 30, 1972 . . . .

Type Agreement: . Letter/Memorandum dated May 25, 1971 . . . . . . Amount: $ 1,999.00 . . . .

Reports Required: Semi-Annual Progress Report
Annual Progress Report
Final Summary Report

Contact Person: Mr. Robert G. Martin
Assistant Executive Vice President
Sport Fishing Institute
719 Thirteenth St., N. W. (Suite 503)
Washington, D. C. 20005

Phone: (202) 737-0668

*This project will be funded at a total estimated cost of $9,530 with $1,999 provided by Sport Fishing Institute, $5,001 by Georgia Games and Fish Commission, and $2,530 by Georgia Institute of Technology.

Assigned to . . . . Electronics (Radar Branch) . . . . Division

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RA-62(12-66)

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station

PROJECT TERMINATION

Date May 3, 1973

PROJECT TITLE: A Study of the Effects of Electric Currents on Fish

PROJECT NO: B-397

PROJECT DIRECTOR: Dr. J. L. Edwards

SPONSOR: Sport Fishing Institute; Washington, D. C.

TERMINATION EFFECTIVE: 5/2/73 (Final Report submitted)

CHARGES SHOULD CLEAR ACCOUNTING BY: N/A - all funds expended

Grant Closeout Itmes Remaining: None

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Form EES 402 (R10-62)

B-397

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION 225 North Avenue, Northwest · Atlanta, Georgia 30332

15 October 1971

Mr. Robert G. Martin
Asst. Executive Vice President
Sport Fishing Institute
719 Thirteenth Street, N.W.
Suite 503
Washington, D. C. 20005

Re: October 15 Status Report

Dear Bob:

Enclosed is the October 15 report on the status of the "Study of the Effects of Electric Currents on Fish" as required by our Memorandum of Understanding. As you know, the Georgia State Game & Fish Commission is providing over half of the support for this study. Their participation has been delayed, largely because of an extended illness suffered by Leon Kirkland, the Chief of Fisheries, during the summer months. He has now recovered and contractual arrangements with the Commission are being completed this week. Although some work has been done on the Study, the bulk of it has had to be delayed until Commission support was assured, since they are to provide the majority of the funding. Full cooperation of the Commission, on both technical and administrative levels, has now been assured, and work will begin in earnest during the next few weeks. It is expected that the Study will be carried to completion well within the scheduled period.

A quarterly report will be issued to the Commission in January and a copy will be sent to you at that time. Meanwhile, if there is any further information which we can give you, please do not hesitate to write or call me at (404) 873-4211, Ext. 163 (after November 25 (404) 894-3521).

Sincerely yours,

J. L. Edwards

JLE:bp

Enclosures

cc: Mr. Leon Kirkland

STATUS REPORT

Title: "Study of the Effects of Electric Currents on Fish"

Reference: A Project undertaken for the Sport Fishing Institute and the Georgia State Game and Fish Commission by the Georgia Institute of Technology

Date: 15 October 1971

The purpose of this study is to measure in controlled laboratory experiments the reactions of a few species of local fresh-water fish to various types of direct, alternating and pulsating electric currents. Most state game and fish departments already utilize some sort of electrical apparatus for sampling fish populations, and the knowledge gained through this study can be used to improve the efficiency, the extent of coverage, and possibly the selectivity of electrical techniques. For a fuller explanation of the program, reference is made to the proposal dated 30 March 1971 submitted by Georgia Tech to the Sport Fishing Institute.

The study has been divided into six tasks as follows:

(1) A literature survey to determine pertinent results which have been already recorded.

(2) The design and construction of a pulse generator to produce unipolar pulses of variable shape and duration at appropriate voltages and pulse rates.

(3) The installation and stocking of an experimental fish tank, to be done with the direct assistance of the Georgia State Game and Fish Commission. The tank will be supplied with an aerator and a temperature control device, and will be instrumented with a thermometer, a device for measuring the conductivity of the water, and any other needed instrumentation.

(4) The design and construction of electrodes for the tank.

(5) The collection of data on the responses of fish as a function of the appropriate parameters.

(6) The submission of a final technical report and any other reporting material required by the sponsors.

The study is being sponsored collectively by the Sport Fishing Institute, the Georgia State Game and Fish Commission, and the Georgia Institute of Technology. Participation by the Georgia State Game and Fish Commission has been delayed for several months, largely because of an extended illness of the Chief of Fisheries. Contractual formalities are being completed only this week, and since the Commission is providing more than half of the support required for this study, it has also been necessary to delay work on the program. However, progress has already been made on the first two tasks as outlined below.

The literature survey has been initiated through the extensive facilities of Georgia Tech's Price Gilbert Memorial Library. A manual search, which will continue for several more weeks, has already unearthed a number of pertinent papers; a list of a few of the more important references is attached. A computer-based search of published literature utilizing the University of Georgia's Information Dissemination Center has also been initiated and is expected to turn up most articles of recent issue.

The initial steps have been taken in the design of a pulse generator to produce the required electrical pulses. Several possible designs are being considered, including a computer-controlled pulse-shaping technique. The

Electronics Division owns a Data General Super Nova Computer which could be used for such a purpose if this design alternative is chosen.

A tentative choice has also been made of the four species of fish which are to be studied. They are 1) large mouth bass, 2) blue gill bream, 3) catfish, 4) sucker or alternatively crappie. If funds are sufficient, both sucker and crappie will be studied and possibly bowfin can be added to the list.

Now that contractual arrangements with the Georgia State Game & Fish Commission are essentially complete, work can and will be undertaken at an increased rate of effort. The program for the next quarter includes the following items:

(1) Completion of the literature survey to determine pertinent results which have already been recorded.

(2) Completion of design of pulse generator for production of pulses of the desired voltages, shapes, durations and repitition rates. Construction of the pulse generator is also expected to commence during this quarter.

(3) Installation of the experimental fish tank along with all required instrumentation and accessories: aerator, temperature control mechanism, thermometer, conductivity meter, etc.

(4) Design of electrodes for the tank. Construction of electrodes is also expected to commence during this quarter.

(5) Detailed definition of the parameters to be observed when fish are exposed to electric currents. These determinations will

be made with the assistance of Biologists from the Georgia State & Fish Commission.

At the planned rate of effort, it is expected that the study will be completed well within the scheduled period.

Respectfully submitted,

J. L. Edwards
Senior Res. Phys.

Approved:

H. A. Ecker
Head, Radar Branch

PARTIAL LIST OF REFERENCES

1. Northrop, Robert B., "Electrofishing," IEEE Transactions on Bio-Medical Engineering, Vol. BME-14, No. 3, p. 191-200 (1967).

2. Burnet, A.M.R., "Electric Fishing with Pulsatory Direct Current," New Zealand Journal of Science 2, p. 46-56 (1959).

3. Dale, Harry P., "Electronic Fishing with Underwater Pulses," Electronics 32, No. 4, pp. 31-33 (1959).

4. Van Harreveld, A., "On Galvanotropism and Oscillotaxis in Fish," Journal of Experimental Biology 15, pp. 197-208, (1938).

5. Vibert, R., "Fishing with Electricity," Fishing News (Books) Ltd., London, 1967.

6. Kreutzer, C. O., "Electro-fishing Apparatus," U. S. Patent No. 2,850,832 (1958).

B-397

STATUS REPORT - Project B-397

Title: "Study of the Effects of Electric Currents on Fish"

Reference: A project undertaken for the Sport Fishing Institute and the Georgia State Game and Fish Commission by the Georgia Institute of Technology

Date: 30 March 1972

The purpose of this study is to measure in controlled laboratory experiments the reactions of a few species of local fresh-water fish to direct, alternating, and pulsating electric currents of various characteristics. The knowledge gained through this study may be useful in improving the efficiency, extent of coverage, and possibly the selectivity of electrical techniques for sampling fish populations. For a more thorough explanation of the program, reference is made to the proposal dated 30 March 1971 submitted by Georgia Tech to the Sport Fishing Institute.

The study has been organized into the following six tasks.

(1) A literature survey to determine pertinent results which have already been recorded.

(2) The design and construction of a pulse generator to produce unipolar pulses of variable shape and duration at appropriate voltages and pulse rates.

(3) The installation, instrumentation and stocking of experimental fish tanks, to be done with the direct assistance of the Georgia State Game and Fish Commission.

(4) The design and construction of electrodes for the tank.

(5) The collection of data on the responses of fish as a function of the appropriate parameters.

(6) The submission of a final technical report and any other reporting material required by the sponsors.

The present status of work on these six tasks is outlined below.

The literature survey has been essentially completed with the collection of many pertinent papers through Georgia Tech's Price Gilbert Memorial Library and the University of Georgia's Information Dissemination Center. Several additional papers of interest have been collected through personal contacts with other research workers in this field. Contacts with biologists at two laboratories of the National Marine Fisheries Service and with workers at the University of Michigan have been particularly helpful. A continuing awareness of current literature will be maintained throughout the duration of the project.

A pulse generator is now under construction for the production of unipolar pulses at frequencies which can be varied throughout the low audio range, which is the range of interest. The generator will have a capability for "dual frequency" operation, a mode which has been found particularly advantageous by several research workers (e.g., A.M.R. Burnet in New Zealand and the group at the University of Michigan). The generator will be capable of producing pulses of several different shapes, including rectangular, triangular, and exponential. Rectified and unrectified sine waves and constant (d.c.) voltages will also be utilized in tests of comparative effectiveness.

Two fish tanks have been installed and fitted with aerators. The fish in one tank are used for experimentation, and those in the other tank constitute a control group for comparison, especially of mortality rates. Thermometers, chemical monitoring equipment for pH, dissolved oxygen, and hardness, and a conductivity meter have been supplied for the tanks by the Georgia

State Game and Fish Commission. In addition, electronic equipment has been installed to monitor and record on a continuous basis the dissolved oxygen content, pH, conductivity, and temperature of the water.

A set of electrodes has been constructed and installed in the experimentation tank.

Preliminary data have been collected on the responses of five-inch to seven-inch channel catfish to the 60 Hertz half-rectified sine wave output of a portable "back pack" fish shocker supplied by the Georgie State Game and Fish Commission. One hundred ten fish were placed in the experimental tank and an equal number in the control tank. Those in the experimental tank were readily narcotized by a comparatively low-level pulsating field. Most fish appeared to recover immediately when the field was turned off, although about ten percent required five to fifteen mibutes to recover. Occasionally, a few fish failed to recover. Each fish in the experimental tank was subjected to ten to fifteen narcotizing shocks during a two-week period. The few which failed to recover were immediately removed so as not to contaminate the tank. Although most of the fish appeared to recover in a few minutes from the effects of the electrical shocks, the subsequent rate of activity of this group under normal conditions was reduced noticably in comparison to the rate of activity of the fish in the control tank. At the end of a five week period, every fish which had been subjected to the series of shocks had died while virtually all those in the control tank survived. This fact suggests that the series of shocks left residual effects which were not immediately apparent but which eventually caused death. It should be emphasized that this statement is a suggestion, not a conclusion, but the results do indicate a need for careful observations of mortality rates.

The work remaining to be accomplished includes the following items.

(1) Completion of the pulse generator.

(2) Collection and analysis of data on the responses of fish as a function of the appropriate electrical and environmental parameters.

(3) Submission of a final technical report and any other reporting material required by the sponsors.

Work is progressing satisfactorily toward the completion of these tasks.

Respectfully submitted,

J. Lee Edwards
Senior Research Physicist

Approved:

H. A. Ecker
Chief, Radar Division

JLE:sp

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION 225 North Avenue, Northwest · Atlanta, Georgia 30332

13 January 1972

Georgia State Game & Fish Commission
270 Washington Street
Atlanta, Georgia 30334

Attention: Mr. Leon Kirkland, Chief of Fisheries

Dear Mr. Kirkland:

Enclosed are two copies of the First Quarterly Progress Report on the "Study of the Effects of Electric Currents on Fish." The project is moving along well now and we hope to be able to start experimenting with live fish before too long.

I hope that the revised SIE forms we submitted were satisfactory and that they reached you in sufficient time. I am sure you would have let me know if this were not the case.

With best wishes for the New Year.

Sincerely,

Lee Edwards
Senior Research Physicist

LE:sp

Enclosures

FIRST QUARTER PROGRESS REPORT - Project B-400

Title: "Study of the Effects of Electric Currents on Fish"

Reference: A Project undertaken for the Georgia State Game and Fish Commission and the Sport Fishing Institute by the Georgia Institute of Technology

Date: 1 December 1971

The purpose of this study is to measure in controlled laboratory experiments the reactions of a few species of local fresh-water fish to various types of direct, alternating and pulsating electric currents. Most state game and fish departments already utilize some sort of electrical apparatus for sampling fish populations, and the knowledge gained through this study can be used to improve the efficiency, the extent of coverage, and possibly the selectivity of electrical techniques. For a fuller explanation of the program, reference is made to the proposal dated 30 March 1971 submitted by Georgia Tech to the Georgia State Game and Fish Commission.

The study has been divided into six tasks as follows:

(1) A literature survey to determine pertinent results which have been already recorded.

(2) The design and construction of a pulse generator to produce unipolar pulses of variable shape and duration at appropriate voltages and pulse rates.

(3) The installation and stocking of an experimental fish tank, to be done with the direct assistance of the Georgia State Game and Fish Commission. The tank will be supplied with an aerator and a temperature control device, and will be

instrumented with a thermometer, a device for measuring the conductivity of the water, and any other needed instrumentation.

(4) The design and construction of electrodes for the tank.

(5) The collection of data on the responses of fish as a function of the appropriate parameters.

(6) The submission of a final technical report and any other reporting material required by the sponsors.

The study is being sponsored collectively by the Georgia State Game and Fish Commission, the Sport Fishing Institute, and the Georgia Institute of Technology. Formalities of the contract between the Commission and Georgia Tech were completed late in October and the progress which has been made on the project since that time is outlined below.

The literature survey was undertaken through the facilities of Georgia Tech's Price Gilbert Memorial Library, and a large number of pertinent papers has been collected. Personal contact has been established with several other research workers in this area including biologists in the National Marine Fisheries Service Laboratories in Seattle, Washington, and Rohwer, Arkansas, and workers at the University of Michigan. These contacts have provided quite a number of useful reports. A computer-based search of recently published literature has been made through the University of Georgia's Information Dissemination Center, and several pertinent reports have been discovered in this way. The literature survey is now largely complete, but a continuing awareness of current literature will be maintained throughout the duration of the project.

The initial steps have been taken in the design of a pulse generator to produce the required electrical pulses. Several possible designs are being considered, including a computer-controlled pulse-shaping technique. The Electronics Division owns a Data General Super Nova Computer which could be used for such a purpose if this design alternative is chosen.

Two identical ten-foot diameter fish tanks have been installed at Georgia Tech, one for use in the experimentation with fish, and the other for a control group of fish, which will be used in comparing mortality rates. These tanks will be provided with aerators, temperature control devices and all necessary instrumentation.

A choice has been made of the four species of fish which are to be studied. They are 1) large mouth bass, 2) blue gill bream, 3) catfish, and 4) sucker or alternatively crappie. If funds are sufficient, both sucker and crappie will be studied and possibly bowfin can be added to the list.

The program for the next quarter includes the following items:

(1) Completion of the literature survey to determine pertinent results which have already been recorded.

(2) Completion of design of pulse generator for production of pulses of the desired voltages, shapes, durations and repitition rates. Construction of the pulse generator is also expected to commence during this quarter.

(3) Outfitting of the experimental fish tank with all required instrumentation and accessories: aerator, temperature control mechanism, thermometer, conductivity meter, etc.

(4) Design of electrodes for the tank. Construction of electrodes is also expected to commence during this quarter.

(5) Detailed definition of the parameters to be observed when fish are exposed to electric currents. These determinations will be made with the assistance of Biologists from the Georgia State Game & Fish Commission.

At the planned rate of effort, it is expected that the study will be completed well within the scheduled period.

Respectfully submitted.

J. L. Edwards
Senior Research Physicist

Approved:

H. A. Ecker
Head, Radar Branch

B-400

SECOND QUARTER PROGRESS REPORT - Project B-400

Title: "Study of the Effects of Electric Currents on Fish"

Reference: A project undertaken for the Georgia State Game and Fish Commission and the Sport Fishing Institute by the Georgia Institute of Technology

Date: 1 March 1972

The purpose of this study is to measure in controlled laboratory experiments the reactions of a few species of local fresh-water fish to direct, alternating, and pulsating electric currents of various characteristics. The knowledge gained through this study may be useful in improving the efficiency, extent of coverage, and possibly the selectivity of electrical techniques for sampling fish populations. For a more thorough explanation of the program, reference is made to the proposal dated 30 March 1971 submitted by Georgia Tech to the Georgia State Game and Fish Commission.

The study has been organized into the following six tasks.

(1) A literature survey to determine pertinent results which have already been recorded.

(2) The design and construction of a pulse generator to produce unipolar pulses of variable shape and duration at appropriate voltages and pulse rates.

(3) The installation, instrumentation and stocking of experimental fish tanks, to be done with the direct assistance of the Georgia State Game and Fish Commission.

(4) The design and construction of electrodes for the tank.

(5) The collection of data on the responses of fish as a function of the appropriate parameters.

(6) The submission of a final technical report and any other reporting material required by the sponsors.

The present status of work on these six tasks is outlined below.

The literature survey has been essentially completed with the collection of many pertinent papers through Georgia Tech's Price Gilbert Memorial Library and the University of Georgia's Information Dissemination Center. Several additional papers of interest have been collected through personal contacts with other research workers in this field. Contacts with biologists at two laboratories of the National Marine Fisheries Service and with workers at the University of Michigan have been particularly helpful. A continuing awareness of current literature will be maintained throughout the duration of the project.

A pulse generator is now under construction for the production of unipolar pulses at frequencies which can be varied throughout the low audio range, which is the range of interest. The generator will have a capability for "dual frequency" operation, a mode which has been found particularly advantageous by several research workers (e.g., A.M.R. Burnet in New Zealand and the group at the University of Michigan). The generator will be capable of producing pulses of several different shapes, including rectangular, triangular, and exponential. Rectified and unrectified sine waves and constant (d.c.) voltages will also be utilized in tests of comparative effectiveness.

Two fish tanks have been installed and fitted with aerators. The fish in one tank are used for experimentation, and those in the other tank constitute a control group for comparison, especially of mortality rates. Thermometers, chemical monitoring equipment for pH, dissolved oxygen, and hardness, and a conductivity meter have been supplied for the tanks by the Georgia

State Game and Fish Commission. In addition, electronic equipment has been installed to monitor and record on a continuous basis the dissolved oxygen content, pH, conductivity, and temperature of the water.

A set of electrodes has been constructed and installed in the experimentation tank.

Preliminary data have been collected on the responses of five-inch to seven-inch channel catfish to the 60 Hertz half-rectified sine wave output of a portable "back pack" fish shocker supplied by the Georgie State Game and Fish Commission. One hundred ten fish were placed in the experimental tank and an equal number in the control tank. Those in the experimental tank were readily narcotized by a comparatively low-level pulsating field. Most fish appeared to recover immediately when the field was turned off, although about ten percent required five to fifteen mibutes to recover. Occasionally, a few fish failed to recover. Each fish in the experimental tank was subjected to ten to fifteen narcotizing shocks during a two-week period. The few which failed to recover were immediately removed so as not to contaminate the tank. Although most of the fish appeared to recover in a few minutes from the effects of the electrical shocks, the subsequent rate of activity of this group under normal conditions was reduced noticably in comparison to the rate of activity of the fish in the control tank. At the end of a five week period, every fish which had been subjected to the series of shocks had died while virtually all those in the control tank survived. This fact suggests that the series of shocks left residual effects which were not immediately apparent but which eventually caused death. It should be emphasized that this statement is a suggestion, not a conclusion, but the results do indicate a need for careful observations of mortality rates.

The work remaining to be accomplished includes the following items.

(1) Completion of the pulse generator.

(2) Collection and analysis of data on the responses of fish as a function of the appropriate electrical and environmental parameters.

(3) Submission of a final technical report and any other reporting material required by the sponsors.

Work is progressing satisfactorily toward the completion of these tasks.

Respectfully submitted,

J. Lee Edwards
Senior Research Physicist

Approved:

H. A. Ecker
Chief, Radar Division

JLE:sp

B-400

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION 225 North Avenue, Northwest · Atlanta, Georgia 30332

23 June 1972

Georgia Department of Natural Resources
270 Washington Street
Atlanta, Georgia 30334

Attention: Mr. Leon Kirkland, Chief of Fisheries

Subject: Third Quarterly Progress Report
Project B-400
"A Study of the Effects of Electric Currents on Fish"

Dear Mr. Kirkland:

This study has been divided into six tasks as outlined in the proposal and in the previous progress reports. A summary of progress made on each of these tasks during the period March 1 through May 31 is outlined below.

Technical Progress

1. Literature Survey

The literature survey, as reported in the previous progress report, is essentially complete, but the search of current literature has been maintained.

2. Pulse Generator

The pulse generator for the production of unipolar pulses has been constructed and passed its checkout tests. The generator is a highly flexible laboratory instrument capable of producing rectangular pulses with a variable duty factor and exponential pulses with a variety of time constants. Peak voltages up to 200 V. and peak currents of 2 amps or more can be obtained at frequencies from a few Hertz to 200 Hz. The pulse strings can be uninterrupted or they can be interrupted periodically at a variable frequency. This feature provides the capability for "dual frequency" operation which several researchers have found to be advantageous.

3. Tanks, Instrumentation and Stocking

The agitators and monitoring equipment for the fish tanks continue to operate satisfactorily, and continuous records are being automatically made of the dissolved oxygen content, pH value, water temperature, air temperature, and conductivity in the holding tank. The Federal Bureau of Sport Fisheries has indicated a willingness to supply any fish which they have available in hatcheries at Marion, Alabama, and Warm Springs, Georgia. Fish requirements are therefore being supplied from both state and federal sources.

4. Electrodes

Electrodes for the experiments have been rebuilt in order to provide a larger region in which a uniform electric field can be obtained. The field between the electrodes has been measured with a field probe to determine the limits of the region of uniform field. A non-conducting net has been installed to insure that the fish being tested remain within this region.

5. Data

The collection of data on the responses of fish is now commencing, and with a pulse generator capable of such flexibility in its operation, a large quantity of data is anticipated. In order to collect more data and in order to compensate for delays in the initiation of work on this study, a no cost extension of the contract from June 30 to September 30, 1972 has been requested and verbally approved by all sponsors.

6. Final Report

A final technical report on the results of the study will be submitted on or before the extended completion date of the contract.

Visits

Messrs. R. H. Stroud, Executive Vice President, and R. G. Martin, Assistant Executive Vice President of the Sport Fishing Institute visited our facilities on May 18 for an inspection tour and for technical discussions. They happened to be in Atlanta for the annual convention of the SFI. It was a direct result of this visit that federal sources of fish were made available.

Future Effort

Data will be collected on the responses to electric fields of catfish, largemouth bass, bluegill bream, and either crappie or sucker, as outlined in the proposal, and a final technical report on the results will be presented to the sponsors.

Respectfully submitted,

Lee Edwards
Senior Research Scientist

Approved:

H. Allen Ecker
Chief, Radar Division

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION 225 North Avenue, Northwest · Atlanta, Georgia 30332

1 November 1972

Mr. Robert G. Martin
Assistant Executive Vice President
Sport Fishing Institute
608 Thirteenth Street, N. W. (Suite 801)
Washington, D. C. 20005

Subject: October 15 Progress Report on "A Study of the Effects of Electric Currents on Fish", Project B-397

Dear Mr. Martin:

This study was carried out under the joint sponsorship of the Sport Fishing Institute, the Georgia Department of Natural Resources and the Engineering Experiment Station of the Georgia Institute of Technology. As outlined in the proposal of March 1971, the study was divided into six tasks. A summary of the progress made on each of these tasks is given below.

1. Literature Survey

A literature survey has been made to determine pertinent results which have already been reported. The results of this survey have been used in guiding the course of the present study.

2. Pulse Generator

A pulse generator was constructed for the production of unipolar pulses. The generator is a flexible laboratory instrument capable of producing rectangular or exponential pulses of variable length, frequency, and voltage or steady dc voltages. Peak voltages up to 250 volts and peak currents of 2 amperes or more can be obtained at frequencies from a few Hertz to 200 Hertz or at dc. The pulse trains can be interrupted periodically at a variable frequency, if desired. This feature provides the capability for "dual frequency" operation which several researchers have found to be advantageous.

3. Tanks, Instrumentation and Stocking

Two ten-foot diameter tanks were supplied by the Georgia Department of Natural Resources, along with agitators and devices for monitoring conductivity, dissolved oxygen content, pH value, water temperature, and hardness. One tank was used as a holding tank while the other was used for conducting the experiments. Fish were supplied for the experiments through the joint efforts of the Georgia Department of Natural Resourses and the Federal Bureau of Sport Fisheries. The cooperation of the latter agency was obtained directly through the efforts of the Sport Fishing Institute. Fish were obtained from federal hatcheries at Warm Springs, Georgia, Marion, Alabama, and Cohutta, Georgia, and from other sources through the Georgia Department of Natural Resources.

4. Electrodes

Electrodes for the experiments were installed in one of the two fish tanks. It was desirable to obtain a large region of uniform electric field strength in which to conduct the experiments, and the electrodes which were used provided this condition. A non-conducting net was installed to confine the fish to the region in which the electric field was uniform.

5. Data

The collection of data has now been completed on four species of fish common to the lakes and streams of Georgia. Data were collected on two groups of channel catfish averaging 8 inches and 11 inches in length, on two groups or bluegill averaging 2 inches and 6 inches in length, one group of large-mouth bass averaging about 4 inches in length and one group of bowfin averaging about 13 inches in length. Other sizes of bass and bowfin were not available for the conduct of experiments at this time.

The limitations on the availability of fish and the size of holding facilities required that each group of fish be limited to roughly 100 to 200 in number. In order to obtain an acceptable level of statistical reliability in the data, it was necessary to administer 600 to 800 individual shock tests to each group. It was therefore necessary to test each fish several times. In most cases, a recovery time of a day or more could be allowed, and it appeared that the data were not significantly affected by repetitive testing.

The principal goals in collecting the data were to determine, by varying pulse repetition frequency, pulse length, and pulse shape, whether it is possible to achieve:

(1) a significant degree of selectivity with regard to the size or species of fish affected, or

(2) a significant reduction in the average amount of electrical power applied to the water.

Although the analysis of the data has not yet been completed, it appears that the data give little indication that fish can be selected by species through a choice of electrical parameters. However, the data show that larger fish are more susceptible to underwater electric fields than are smaller fish. With regard to the second goal, the data show that, in comparison with dc fields, dramatic reductions in the amount of average power applied to the water can be achieved by pulse techniques. Typical data show that a reduction of 96% can be achieved through the use of interrupted trains of rectangular pulses (dual frequency mode of operation). There is no reason to believe that the limit has been reached, and limited data indicate that even greater reductions may be possible. There is a need to obtain additional data to determine what further reductions are possible, but limitations of time and support funds have not allowed the collection of additional data during the present project.

6. Final Report

A final technical report will be issued by the end of the year to discuss the study and present its findings. All of the results mentioned briefly above will be discussed more fully in the report.

Visits

Messrs. R. H. Stroud, Executive Vice President, and R. G. Martin, Assistant Executive Vice President of the Sport Fishing Institute, visited our facilities on May 18, 1972, for an inspection tour and technical discussions.

Future Effort

Further effort on the present project will be devoted to the completion of data analysis and the final technical report.

An effort will also be made to obtain support for further work to determine whether limited evidence is correct in indicating that further substantial reductions in the amount of average power can be made without reducing the effectiveness of electrical shocking techniques. Such information would be of value because it would enable electrofishing techniques to operate over larger areas or on smaller primary power sources. It is possible that portable "back-pack" shockers, which presently use small gasoline engines to drive generators, could be replaced by smaller dry cell battery-powered units with equal or greater effectiveness. Such units would have as added advantages silent operation and the reliability of solid state circuitry. It seems desirable that such a possibility should be explored.

Respectfully submitted,

Approved:

J. L. Edwards
Senior Research Scientist

H. A. Ecker
Chief, Radar Division

Final Technical Report

Projects B–397, B–400 and E–200–301

THE EFFECTS OF ELECTRIC CURRENTS ON FISH

by

J. L. Edwards and J. D. Higgins

March 1973

Prepared for:

Game and Fish Division
Department of Natural Resources
Atlanta, Georgia 30334

and

Sport Fishing Institute
Washington, D. C. 20005

1973

Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia

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Final Technical Report

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FOREWORD

This research project was conducted by personnel of the Radar Division of the Engineering Experiment Station at the Georgia Institute of Technology. The work was funded jointly by the Game and Fish Division of the Georgia Department of Natural Resources, the Sport Fishing Institute, and the Radar Division. Fish were supplied by the Georgia Department of Natural Resources and by National Hatcheries of The Bureau of Sport Fishing and Wildlife. Equipment for holding and handling fish and for monitoring water conditions was supplied by the Georgia Department of Natural Resources. The authors wish to express their gratitude to the personnel of these agencies whose assistance made this research possible.

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SECTION I

INTRODUCTION

During the last several decades, techniques have been developed for catching and guiding fish with the aid of underwater electric fields. Most state fish and game departments in the U. S., for example, use some type of electrical fishing apparatus in surveying the populations of streams and lakes. Fish can be immobilized with electric currents, then collected by net for counting, and subsequently released to recover unharmed after a few minutes.

Present techniques possess a number of undesirable characteristics: their effect is restricted to a rather small region, they usually operate simply by immobilizing almost all the fish within that limited region, and they are inefficient in their consumption of electrical power.

In order to effect improvements, a number of research programs have been carried out in many parts of the world to study in a systematic way the reactions of fish to electric currents of various types [1-9]. Investigations have been made of the physiological mechanisms responsible for the reactions which are observed. It is clear that the responses often involve the sensory and motor nerve systems, but it appears that the mechanisms are complex and not completely understood at the present time. However, some useful data have been collected during these studies. The reactions which have been observed and reported [1] can be briefly described as follows. The reaction depends partly on the character of the applied electric current. If a steady direct current is passed through the water, at small current densities a fluttering of the fish's entire body is seen. A state of agitation or fright is also frequently observed. At higher current densities, the fish tend to swim involuntarily toward the anode.* At still higher current densities, the fish roll over to one side and are incapable of movement. If an alternating current is used, no tendency is seen to swim toward either electrode, but the fish tend to take up a transverse orientation between the electrodes. At sufficiently high current levels the fish are immobilized. If pulsating direct currents (direct currents which are interrupted and possibly varied with time) are used, similar reactions are observed as with steady direct currents, but the physiological mechanisms responsible for the reactions are thought to be somewhat different.

Not all observers report precisely the same set of reactions, but observations can differ for a variety of reasons. The descriptions given above serve as a typical indication of the responses which have been reported.

Fish of different sizes or of different species exhibit somewhat different sensitivities to electric currents and, in certain cases, different responses. Responses are also affected by the orientation of the fish with respect to the direction of flow of an applied electric current and by the conductivity and temperature of the water.

Earlier work indicates that the reactions most favorable for electrofishing are observed when pulsating direct currents are used [1-6]. As with constant direct currents, fish may be rendered immobile but with substantially less average electrical power. There is evidence that different species of fish exhibit their maximum susceptibilities at different frequencies of pulsation. Fish of different sizes also appear to have their greatest sensitivities at somewhat different frequencies even though they are of the same species.

Electrical impulses play an important role in the activity of fish,

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* See Glossary on page 71 for definitions.

just as they do with other members of the animal kingdom possessing a neuromuscular system. Sensory nerves transmit information about external stimuli to the brain, and electrical impulses transmitted by the brain through a network of motor nerves cause muscles to contract. Externally applied electric currents passing through a fish's body can induce a reaction through either of these nerve systems: by providing stimuli to the sensory nerves causing the brain to send impulses to the muscles, or, more directly, by producing currents in the motor nerves which override signals transmitted by the brain.

A number of investigators [1,7,8] have studied the physiological mechanisms responsible for the reactions of fish to electric currents. The neurological mechanisms mentioned above as well as biochemical mechanisms have been proposed and investigated in attempts to explain the various reactions which have been observed. However, the present study is strictly an empirical one in that measurements of reactions have been made without attempting to identify the response mechanisms.

This study was motivated by an interest in improving electrofishing techniques for population sampling and its goals were twofold: first, to investigate the possibility of selectively affecting a particular species or size of fish by choosing the appropriate waveform and other electrical parameters, and second, to investigate the possibility of reducing average power requirements through the use of pulse shapes and frequencies to which fish exhibit particular sensitivity.

The approach taken in fulfilling the goals was to shock fish under controlled conditions in the laboratory. In this way the electric fields actually applied to the fish could be accurately determined, the paths of the fish could be restricted to a region where their responses were readily observable, and the conditions of the aquatic environment (water temperature, conductivity, dissolved oxygen content, etc.) could be held constant throughout the series of tests.

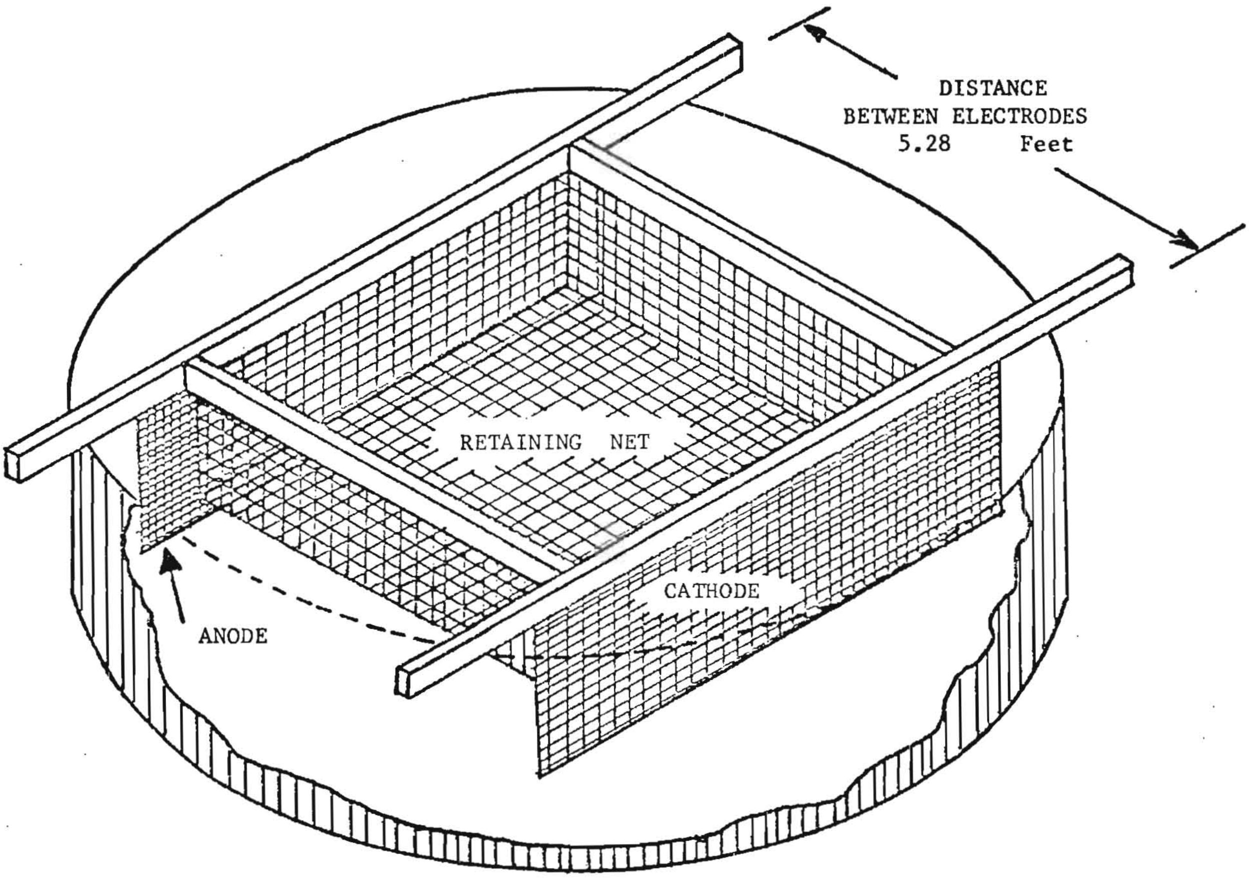
A knowledge of the reactions of fish of various species and sizes to pulsating electrical currents is of obvious practical value for electrofishing. Measurements have been made during the present study of the responses to electrical pulses of four species of freshwater fish indigenous to the streams of Georgia. Responses were measured as a function of the maximum intensity of the electric field produced in the water, the shape of the applied electrical pulses, their frequency of repetition, and the length of the subject fish. Water conditions were held approximately constant throughout the tests. Particular emphasis was placed on the determination of the minimum field strength required to produce immediate immobility or paralysis in 75 percent of the fish of a given size and species for a given set of electrical parameters (pulse shape, frequency, etc.). Results are presented in the following sections.

SECTION II

EXPERIMENTAL APPARATUS

The controlled shocking experiments were conducted in a ten-foot diameter plastic-lined pool filled with water to a depth of about two feet. The electrode configuration used in these tests consisted of two parallel flat plates of hardware cloth (coarse wire screen) placed vertically in the water a little more than five feet apart. (See Figure 1.) An insulating retaining net about five feet square prevented the escape of fish from the test region between the anode and the cathode but did not affect the passage of electric currents through the water. The advantage of such an arrangement is that the electric field strength and current density in the water are uniform throughout the test region and therefore the reaction of a given fish should be the same regardless of its location. Measurements of the electric field showed that it was in fact uniform throughout the test region.

The uniform character of the field assured that the fish under test experienced the same electrical field strength, that is, the same strength of shock, at any location within the retaining net. This fact made the correlation of responses with field strength far simpler than it would have been if the field had not been uniform. For other electrode configurations, the electric field strength at a given point in the water can be determined analytically. Thus, if fish responses are known as functions of field strength, and the electrode configuration is known, the expected response at any point in water can be predicted. When changes in field strength were desired, they were made simply by changing the voltage applied to the electrodes, but still the field strength in the present apparatus was the same at all points within the test region.



FISH SHOCKING FACILITIES

$$\text{Field Strength (Volts/Foot)} = \frac{\text{Voltage Between Electrodes (Volts)}}{\text{Distance Between Electrodes (Feet)}}$$

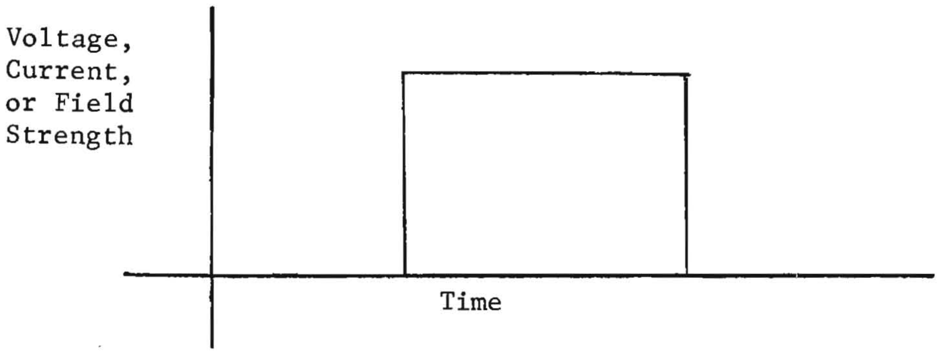
Anode - Positive Electrode
Cathode - Negative Electrode

Figure 1. Fish shocking facilities

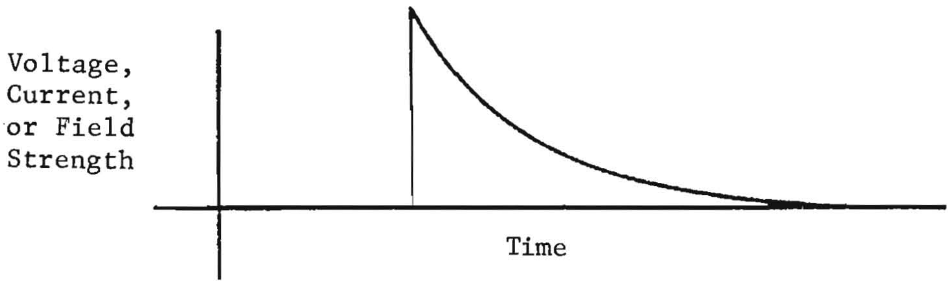
As with any electrode configuration, the shock experienced by a fish depended on its orientation with respect to the direction of flow of electric current in the water: it experienced a greater shock when the axis of its body lay parallel to this direction (perpendicular to the electrodes) than when its axis lay perpendicular to the current flow (parallel to the electrodes).

The specific aims of the series of measurements were to determine whether a waveform (pulse shape and frequency) could be chosen that would be effective in immobilizing one type of fish more than another, and to determine whether the average power required to immobilize fish could be reduced through proper choice of waveform. Accordingly, a versatile laboratory pulse generator was fabricated and used to provide pulses of various shapes, lengths, repetition frequencies, and voltages in order that quantitative comparisions could be made of the effectiveness of different electrical waveforms. Trains of rectangular or exponentially decaying pulses (See Figure 2a and b.) of adjustable length and repetition frequency or a steady dc output could be produced. In addition, a capability was included for interrupting a pulse train periodically to produce what has been referred to as a "dual frequency pulse" [3]. In this mode of operation the pulses were produced in bursts as indicated in Figure 2c. The number of pulses per burst and the interval of time between bursts could be adjusted at will by the operator. Peak voltages up to 260 volts and currents up to 5 amps could be produced. Electric field strengths up to 260 volts/5.28 feet $\approx$ 50 volts/foot could therefore be produced. Figure 3 is a photograph of the equipment used to generate and monitor the various waveforms used in the tests.

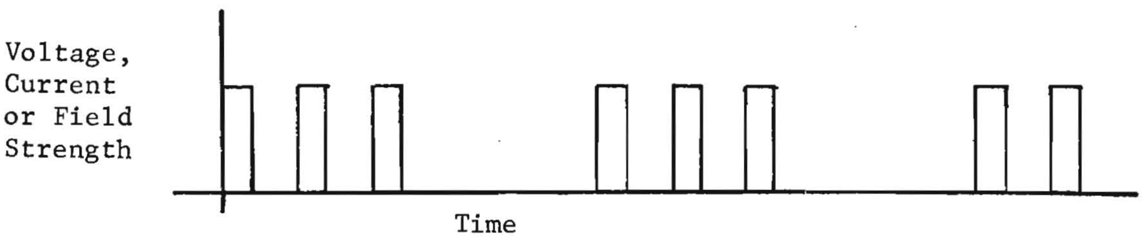
Fish used in these experiments were kept in a second ten-foot diameter



(a) A single rectangular pulse.



(b) A single exponentially decaying pulse.



(c) An interrupted train of rectangular pulses.

Figure 2. Examples of waveforms produced by the experimental pulse generator.

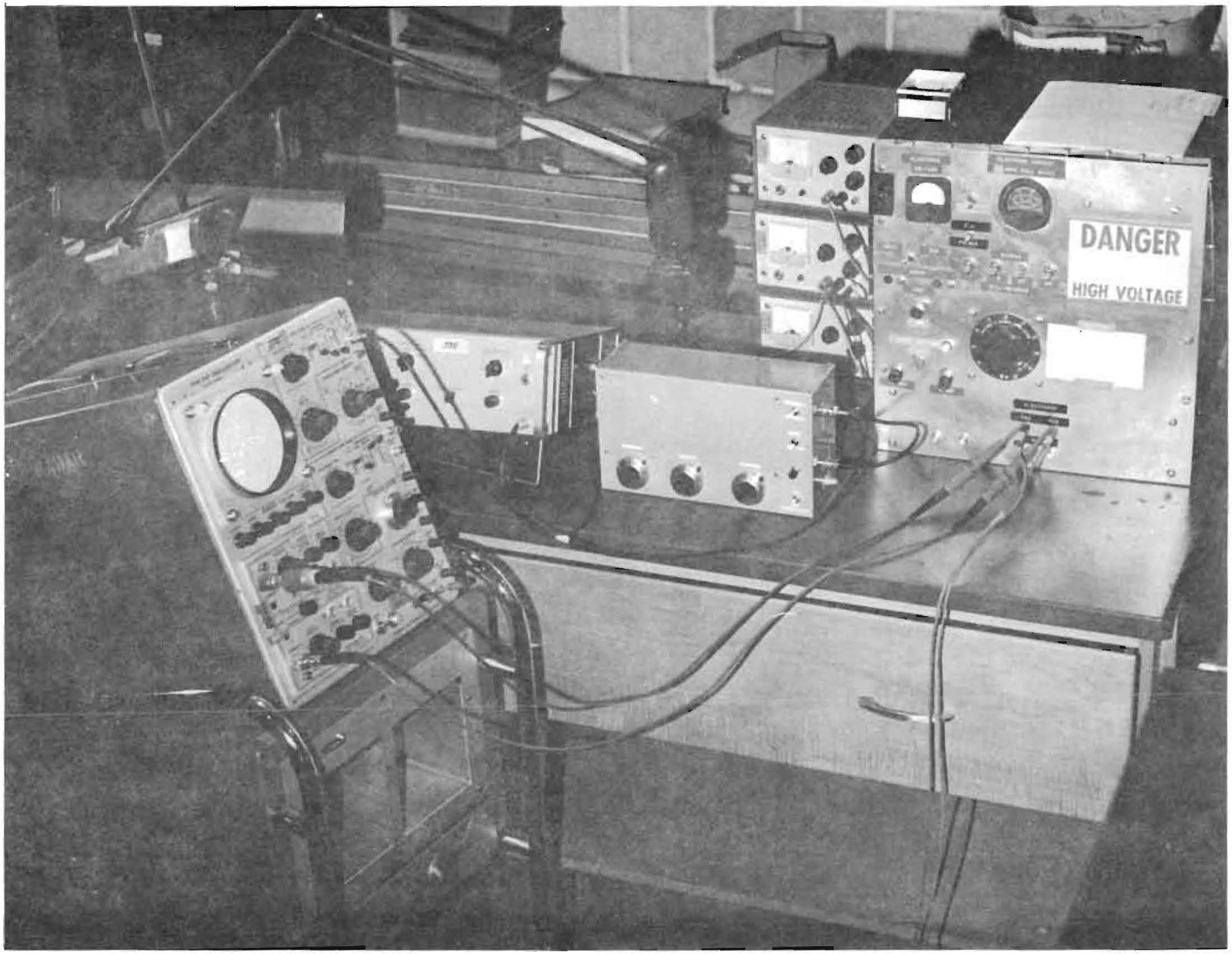


Figure 3. Laboratory Pulse Generator Consisting of (left to right) Oscilloscope for Monitoring Output Waveform, Low voltage Electronic Pulse Generator, Pulse Width Control Box with Circuit for Interrupting Pulse Trains, Three Power Supplies, and the High-voltage, High-power Shocker.

tank (see Figure 4) except while they were actually undergoing shock tests. Dividers of hardware cloth were used to separate the fish into several groups. The water in both tanks was obtained from the City of Atlanta supply. Freshly drawn water was allowed to stand for at least 24 hours before fish were placed in it to allow dissolved chlorine to escape. A sun lamp with substantial ultraviolet emission was also used to drive off the chlorine. Since the pools were inside a heated building, the water temperature remained almost constant, within 2° of 75°F. The dissolved oxygen content was held between 6 and 12 parts per million by rotating vane agitators. The conductivity of the water was measured frequently during the shock tests, and its value remained within 15% of the figure 100 micromhos/centimeter throughout the tests.

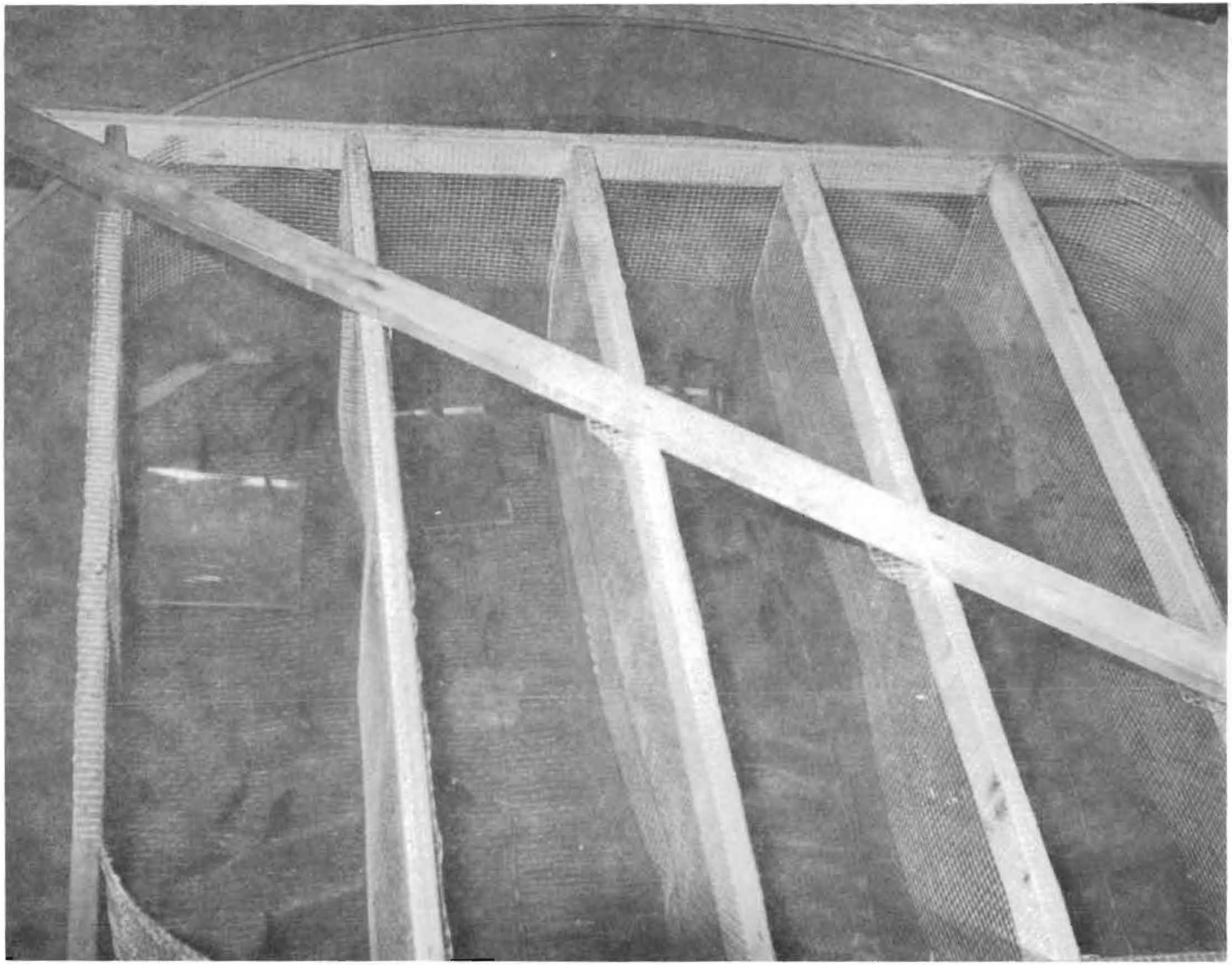


Figure 4. Bluegill in the Holding Pool.

SECTION III

EXPERIMENTAL PROCEDURE

Data were collected characterizing the reactions of each subject species of fish to each of several electrical waveforms (pulse shapes and frequencies, etc.) as a function of the applied electrical field strength. Principal emphasis was placed on the determination of the minimum field strength required to immobilize a particular category of fish when a specific electrical waveform was utilized. However, data on other responses were also collected.

Four species of fish were selected by the Georgia Department of Natural Resources for their pertinence to electrofishing in Georgia, their differences in natural characteristics, and their availability. These species were channel catfish, bluegill, largemouth bass, and bowfin. The first three of these are popular game fish and the fourth is an inedible, undesirable "trash" fish. It was of interest because ways are being sought to reduce its population. In an effort to determine the effect a fish's size might have with regard to its susceptibility to electrofishing, two groups of catfish and two groups of bluegill of different sizes were obtained. These six groups of fish of four different species were subjected to the tests. It was desirable to have all the fish within any one group as near the same size as possible. The range of lengths and the average length of the fish in each group are given, along with other pertinent data, in Table I.

In order to make a quantitative comparison of the effectiveness of different electrical waveforms on a given group of fish, it was necessary to establish an effectiveness criterion. If similar fish had been uniform in their reaction to a given stimulus, it would have been desirable to let the criterion be the minimum or threshold field strength required to immobilize

TABLE I

Fish Group	Range of Lengths (Inches)	Average Length (Inches)	Date Received	Supplied By
Channel Cat I	7 - 15	11	7/25/1972	National Fish Hatchery Marion, Alabama
Channel Cat II	6.5 - 10.5	8.5	8/17/1972	National Fish Hatchery Warm Springs, Georgia
Bluegill I	3 - 8.5	6	8/25/1972	National Fish Hatchery Cohutta, Georgia
Bluegill II	1.5 - 3	2	8/25/1972	National Fish Hatchery Cohutta, Georgia
Largemouth Bass	2.5 - 5	3.5	9/21/1972	National Fish Hatchery Marion, Alabama
Bowfin	11 - 24	16	9/27/1972	Georgia Department of Natural Resources

the fish. However, similar fish often reacted differently to the same stimulus. A field strength that immobilized one fish often served only to excite a similar fish. As with many biological experiments, a statistical treatment of the behavioral data was required. It was decided that an adequate criterion for comparing the effectiveness of different waveforms was the field strength required to immobilize or paralyze 75% of the fish within a group. In order to determine this value of field strength, fish were tested at a range of field strengths spanning the approximate threshold of paralysis. For each waveform at least ten fish were tested at each value of field strength. If, for example, with a particular waveform the data were

0 fish out of 10 paralyzed at 14 volts/foot or less

2 fish out of 10 paralyzed at 15 volts/foot

4 fish out of 10 paralyzed at 16 volts/foot

6 fish out of 10 paralyzed at 17 volts/foot

8 fish out of 10 paralyzed at 18 volts/foot

10 fish out of 10 paralyzed at 19 volts/foot or more

the conclusion would be that a field strength of 17.75 volts/foot was required to paralyze 75% of the fish of this group. This idealized set of data is shown graphically in Figure 5.

Real data rarely followed such a regular pattern as this idealized set. A typical set of real data is shown in Figure 6, the data points for immediate paralysis being shown with the open diamonds. In addition to the data on immediate paralysis, data are also shown on other reactions which were observed. These data points are plotted according to a "Reaction Code" (Table II) which was devised to provide a degree of standardization for the response data.

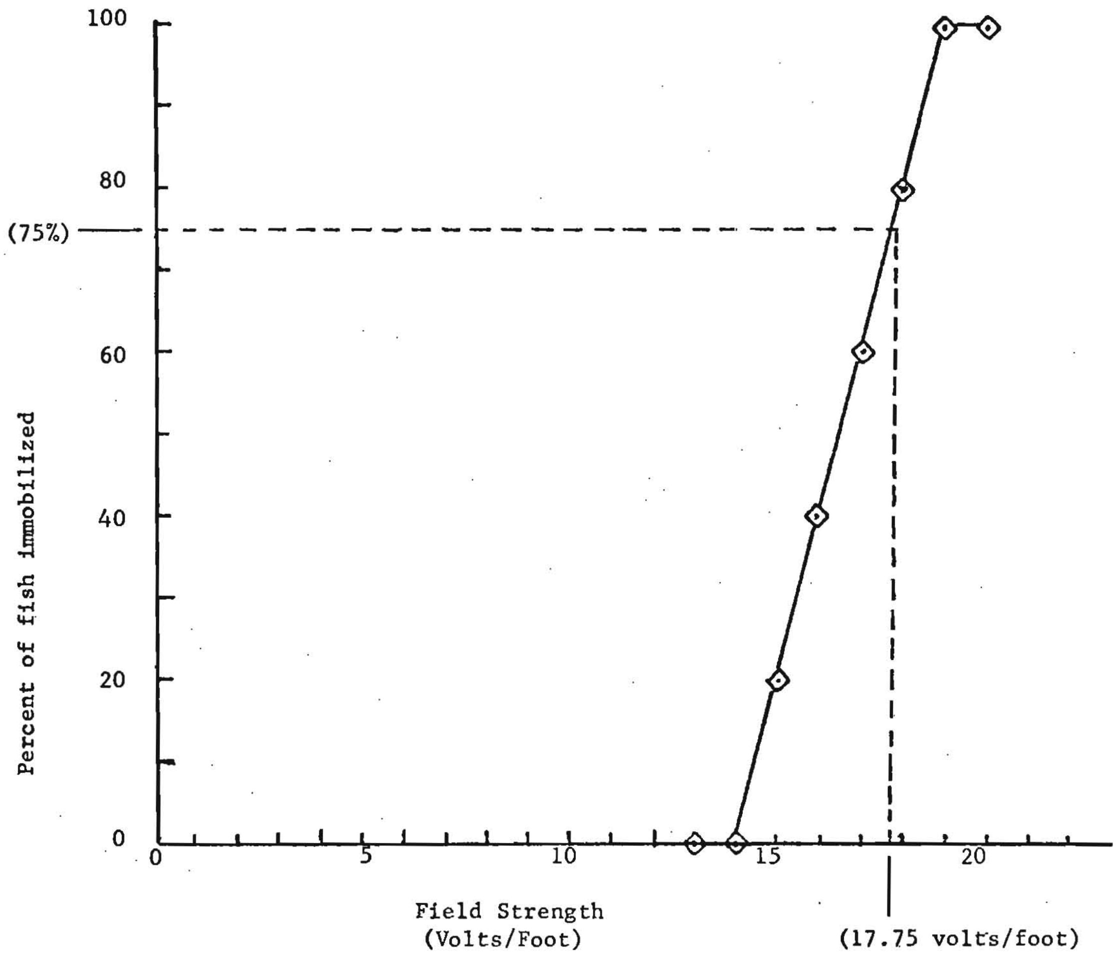


Figure 5. Idealized data set.

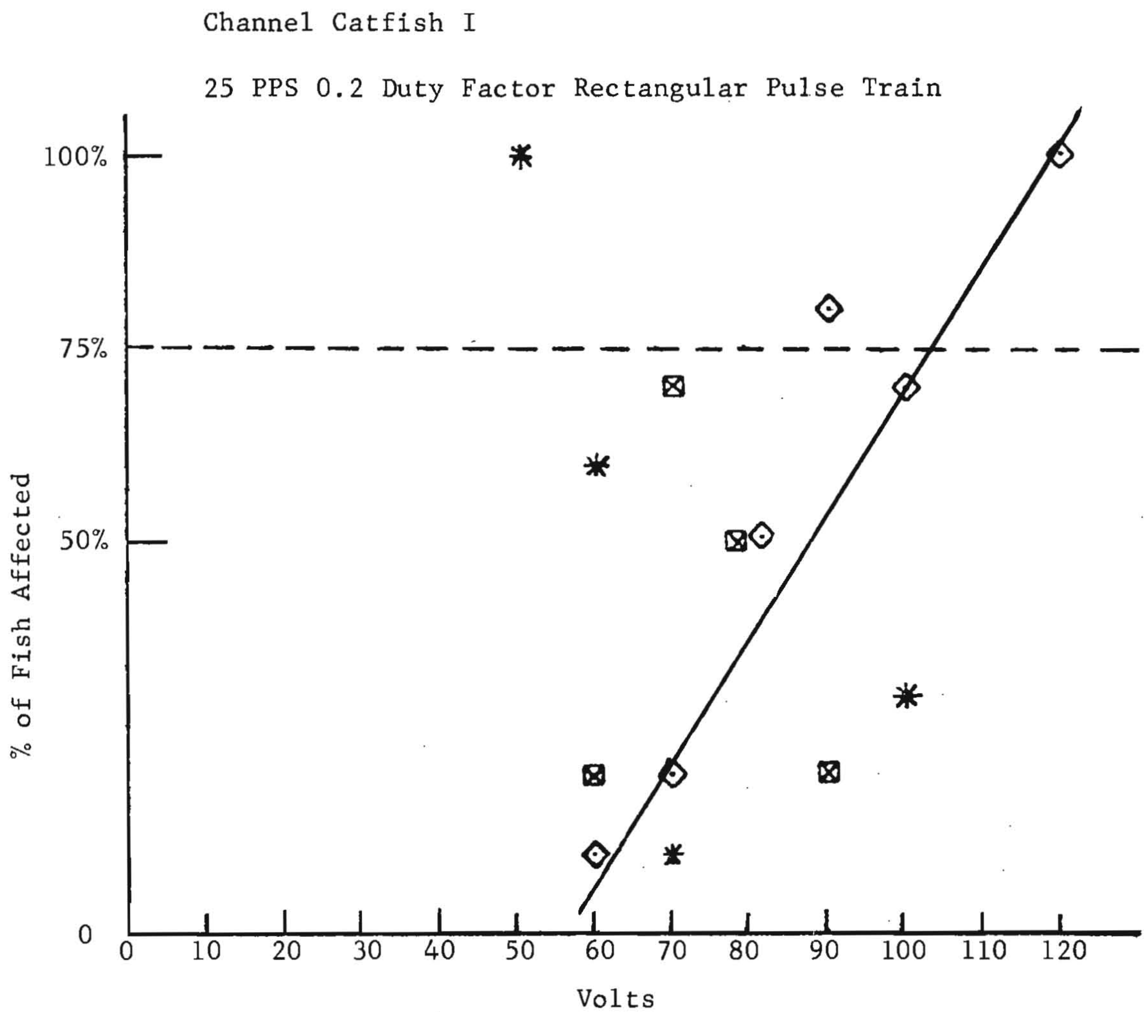


Figure 6. Typical data reduction graph

TABLE II

REACTION CODE

Reaction	No.	Symbol
No effect	0	⊙
Random swimming - excited more than 0	1	+
Alignment along equipotential planes (parallel to electrodes) without paralysis (2* indicating intermittent paralysis)	2	✳
Movement directed toward anode	3	◬
Movement directed toward anode with intermittent paralysis	4	⊡
Paralysis with or without random movement in less than 30 sec. Note time.	5	⊠
Paralysis in less than 10 seconds	6	◇ with a dot inside

This code proved to be reasonably adequate for describing the reactions which were observed.

Each group of fish, with one minor exception, was tested with twelve different waveforms:

(1) steady dc,
(2) rectangular pulses with 0.6 duty factor, 10 pulses per sec.,
(3) rectangular pulses with 0.2 duty factor, 10 pulses per sec.,
(4) rectangular pulses with 0.6 duty factor, 25 pulses per sec.,
(5) rectangular pulses with 0.2 duty factor, 25 pulses per sec.,
(6) rectangular pulses with 0.6 duty factor, 100 pulses per sec.,
(7) rectangular pulses with 0.2 duty factor, 100 pulses per sec.,
(8) rectangular pulses with 0.6 duty factor, 200 pulses per sec.,
(9) rectangular pulses with 0.2 duty factor, 200 pulses per sec.,
(10) "burst" waveform,
(11) exponential pulses with 3.0 ms time constant, 25 pulses per sec.,
(12) exponential pulses with 0.6 ms time constant, 100 pulses per sec.,

The "burst" waveform (10) was identical to waveform (9) except that out of each group of 8 pulses, the last 3 were omitted. All of these waveforms are shown graphically in Figure 7.

The data were collected in the following manner. One to four similar fish were taken by dip net from the holding tank to the shocking tank and placed inside the retaining net. A preset waveform and voltage was then applied with the closure of a switch, and the reactions of the individual specimens were observed and recorded. Electrical power was not applied for more than 30 seconds. The switch was opened, the lengths of the fish were measured, and they were then returned to a different section of the holding tank.

Normally, ten fish were tested at each voltage for each waveform, and six to eight voltages were used with each waveform. The response data were plotted on a graph such as that of Figure 5 or 6 in order to determine the field strength at which 75% of the fish in that group were immobilized. The best straight-line fit to the "reaction 6" data points (diamonds) was plotted

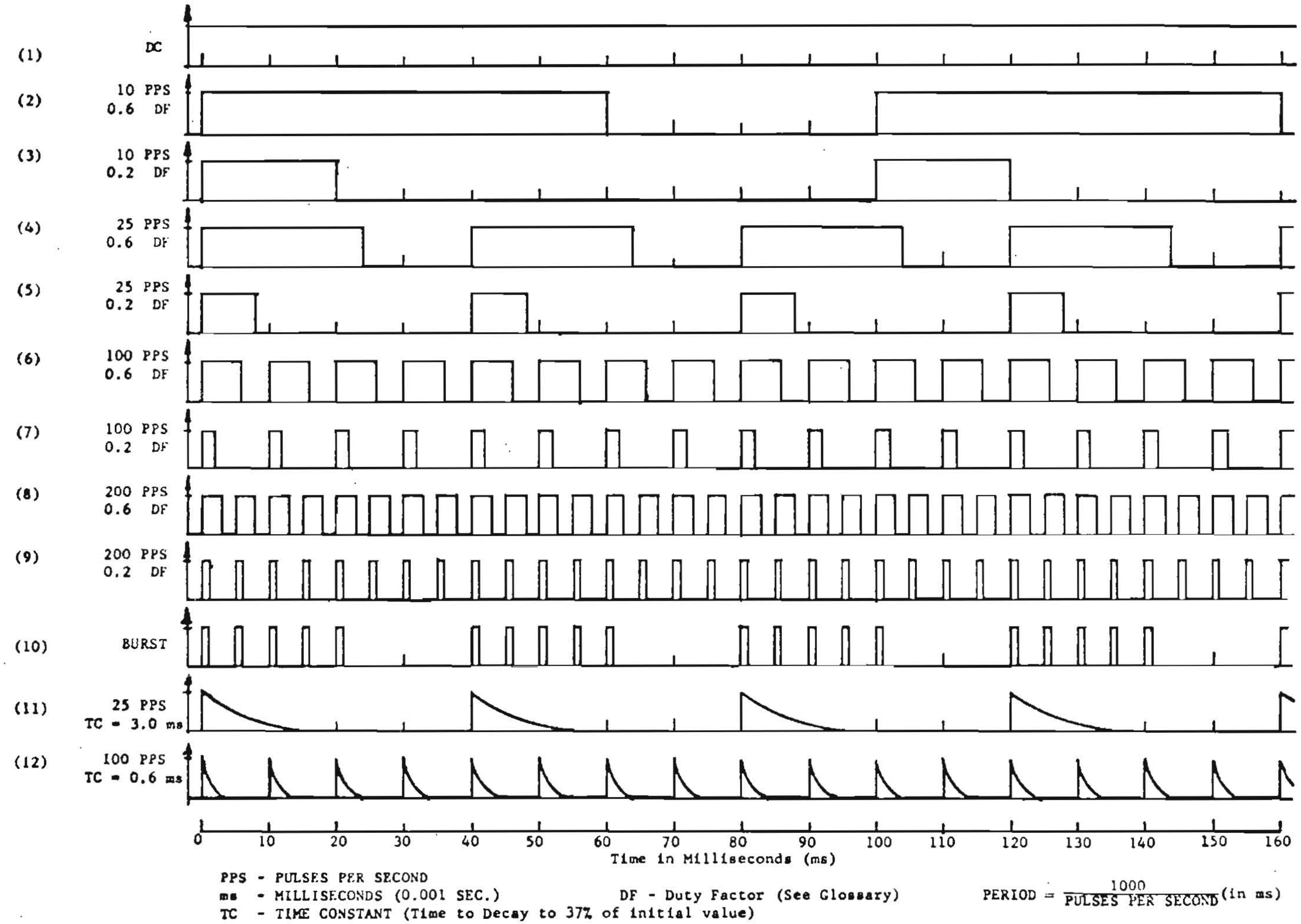


Figure 7. Graphical representations of the various waveforms used.

to determine the field strength corresponding to 75% immobilization. Sixty to eighty fish were tested for each of the twelve waveforms; therefore, 720 to 960 separate shock tests were administered to each group of fish. Holding facilities would not accommodate more than 100 to 300 fish (depending on their size) and so each fish had to be shocked several times. Precautions were taken to see that no fish was shocked twice in the same day. In addition, tests were made to see if susceptibilities of the fish altered after they had experienced several shockings. No significant changes were noted. However, this statement should not be interpreted as indicating that repeated shockings in the field should consistently produce the same results, because, in addition to other factors, there is evidence that experienced fish quickly learn to avoid electrofishing devices. However, with the present experimental arrangement, the fish had no opportunity to avoid being shocked.

Although the reaction of a fish to an electric field depends on its orientation with respect to that field, observations were not recorded of the fishes' orientations. Such observations were felt to be unnecessary because in most cases the fish changed their orientations rapidly and frequently during the tests in a futile effort to escape the field. When not immobilized, they usually found that alignment along equipotential planes (parallel to the electrodes) was the preferable orientation, and in these cases a "reaction 2" was recorded. This reaction proved to be the one most frequently observed at intermediate voltage levels. Occasionally a fish was observed to pass into and out of a state of paralysis as its orientation varied from perpendicular to parallel to the equipotential planes.

The photograph of Figure 8 displays some of these phenomena. Electrodes

Figure 8. Four Bluegill Undergoing Test. Electrodes are at the Top and Bottom in this Picture.

are at the top and bottom of the photograph and the equipotential planes therefore lie parallel to the caption. The two fish at the top are parallel to these planes (the electric current is flowing transversely through their bodies) and they are able to maintain equilibrium. The fish near the center is oriented at right angles to the equipotential planes and is evidently immobilized. The electric current is flowing through its body length-wise and it is experiencing the maximum shock. The fish in the lower right-hand corner is also oriented approximately at right angles to the equipotential planes and might therefore be expected to be paralyzed. The explanation for the fact that it is not may be that it is somewhat smaller than its paralyzed neighbor or that it is simply less susceptible.

Most fish were observed to recover from the shockings either instantly or in a few minutes. The majority of the tests did not cause paralysis of the fish even while the current was being applied, and most of the fish that did suffer paralysis appeared to recover within a few minutes. Very few deaths could be traced directly to the shock tests.

At the beginning of the experimentation, control groups of catfish and bluegill were kept for comparison of mortality rates. These fish were handled in the same way as those undergoing shock, but no shocks were administered. The rates of mortality of the control groups appeared to be about the same as those of the shocked fish for as long as they were kept in the holding tank (about 10 days). Because of the shortage of fish for shock tests and because the shocks appeared to produce no significant change in mortality rates, the procedure of maintaining a control group was eventually abandoned.

SECTION IV

RESULTS

The primary result obtained from the data is a determination of the electric field strength required, with each of the twelve waveforms shown in Figure 7, to immobilize 75% of each group of fish tested. Data on other reactions were also collected, but paralysis was the reaction of greatest interest. The primary effort was therefore directed toward the collection and analysis of data on this reaction. No attempt was made to determine whether the immobility was due to a narcosis, a tetanic condition or to some other cause. All such conditions are useful in electrofishing, and the term "paralysis" is often used in this report to refer to any observed state of immobility.

The bulk of the data were taken with either a dc field or with a rectangular pulse train. In order to determine the frequency dependence of the responses, data were collected at frequencies of 10, 25, 100 and 200 pulses per second. In order to determine the effect of pulse length on the response, duty factors of 0.6 and 0.2 were used at each frequency. (With rectangular pulses, the duty factor is the fraction of time current is on.) Responses to a few other waveforms (two with exponentially decaying pulses and the "burst" waveform) were measured in order to compare the effectiveness of these waveforms with that of the rectangular pulse trains.

The measured field strengths required to paralyze 75% of each group of fish with each of the twelve test waveforms are shown in Figures 9 through 14. Figure 11 shows, for example, that about 52 volts/foot were required to paralyze 75% of the 6" bluegill with a dc current, whereas with rectangular pulses having a duty factor of 0.6, 20 volts/foot were required with 10 pulses per

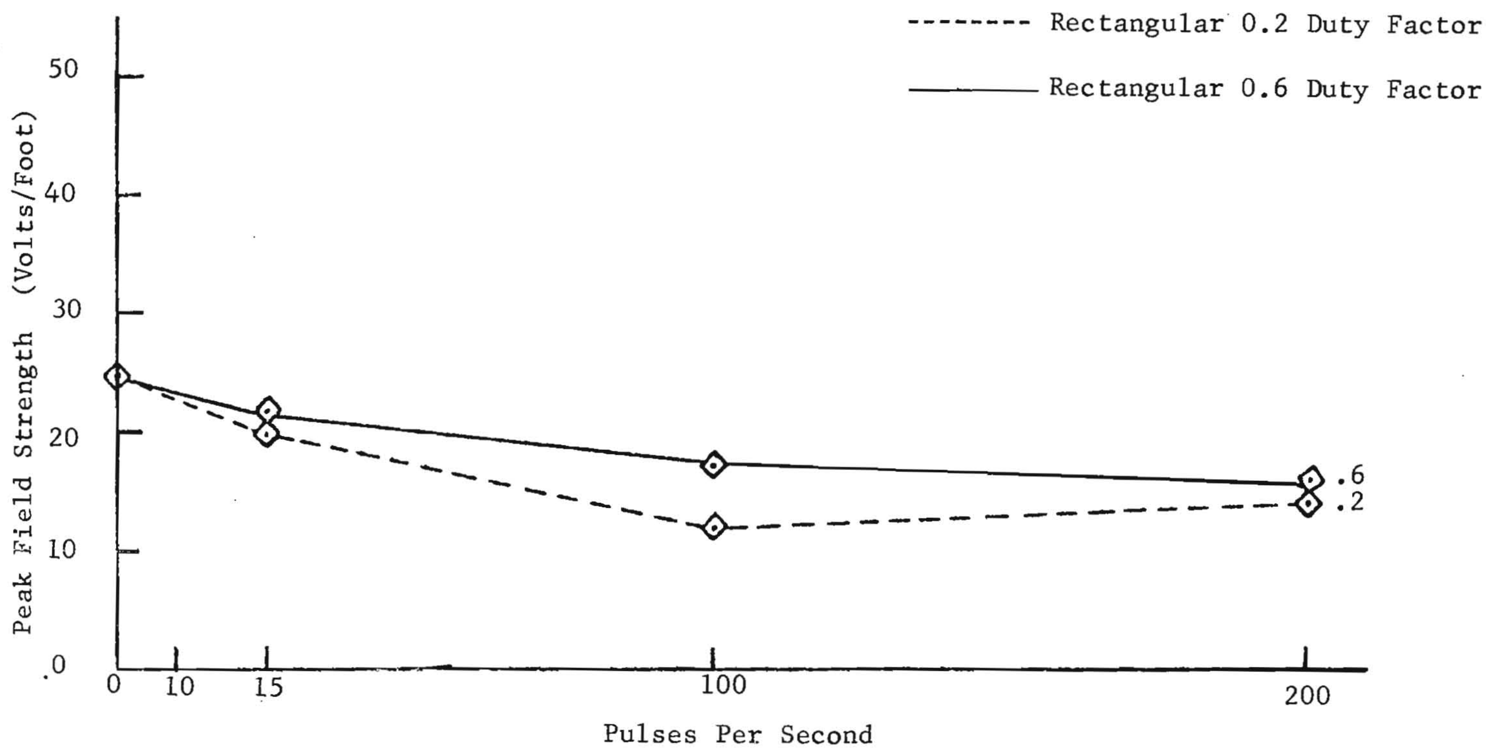


Figure 9. Field strength required to produce 75% immediate paralysis (within 10 seconds) for Channel Catfish I of average length 11" using rectangular pulse trains.

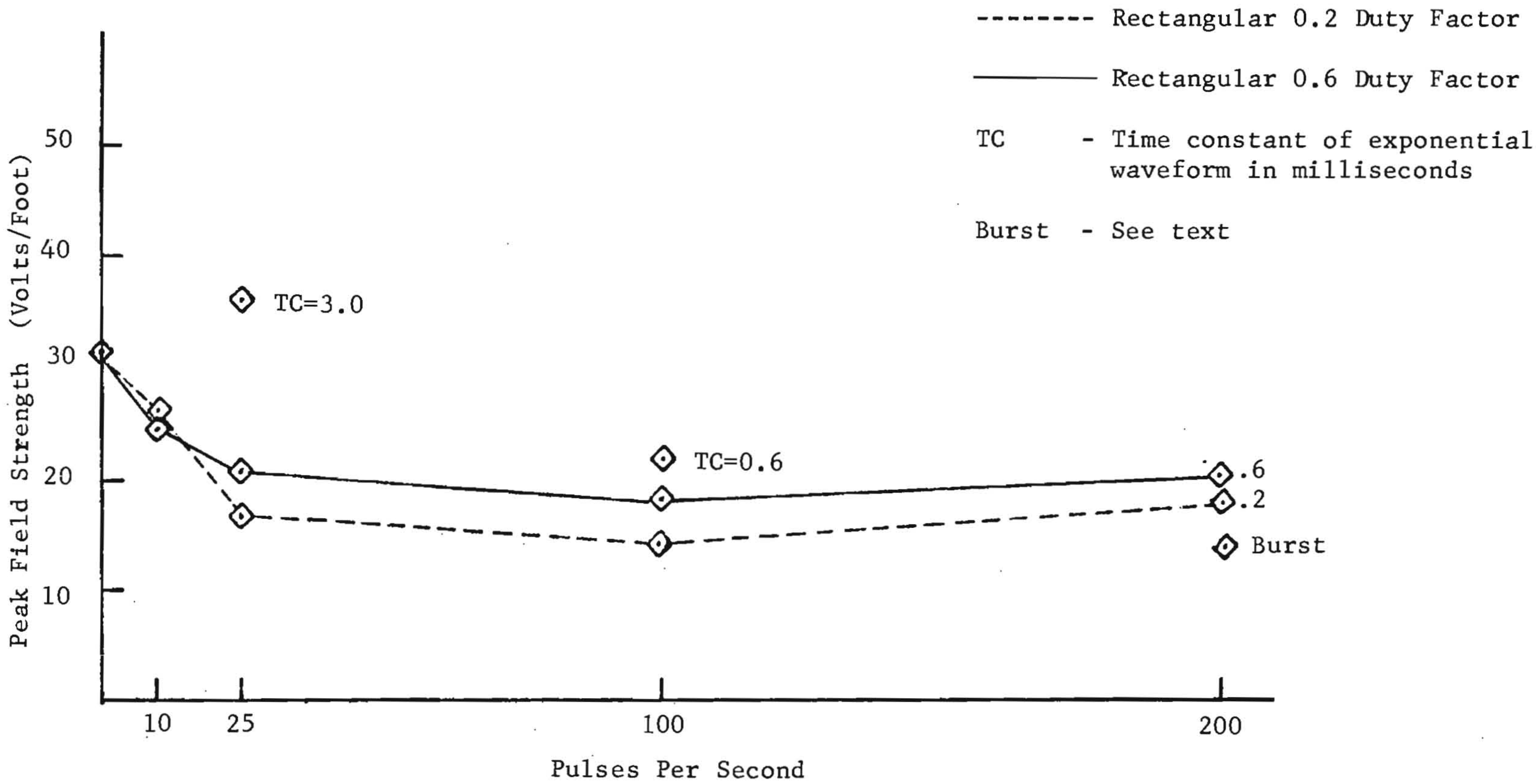


Figure 10. Field strength required to produce 75% immediate paralysis (within 10 seconds) for Channel Catfish II of average length 8.5" using various waveforms.

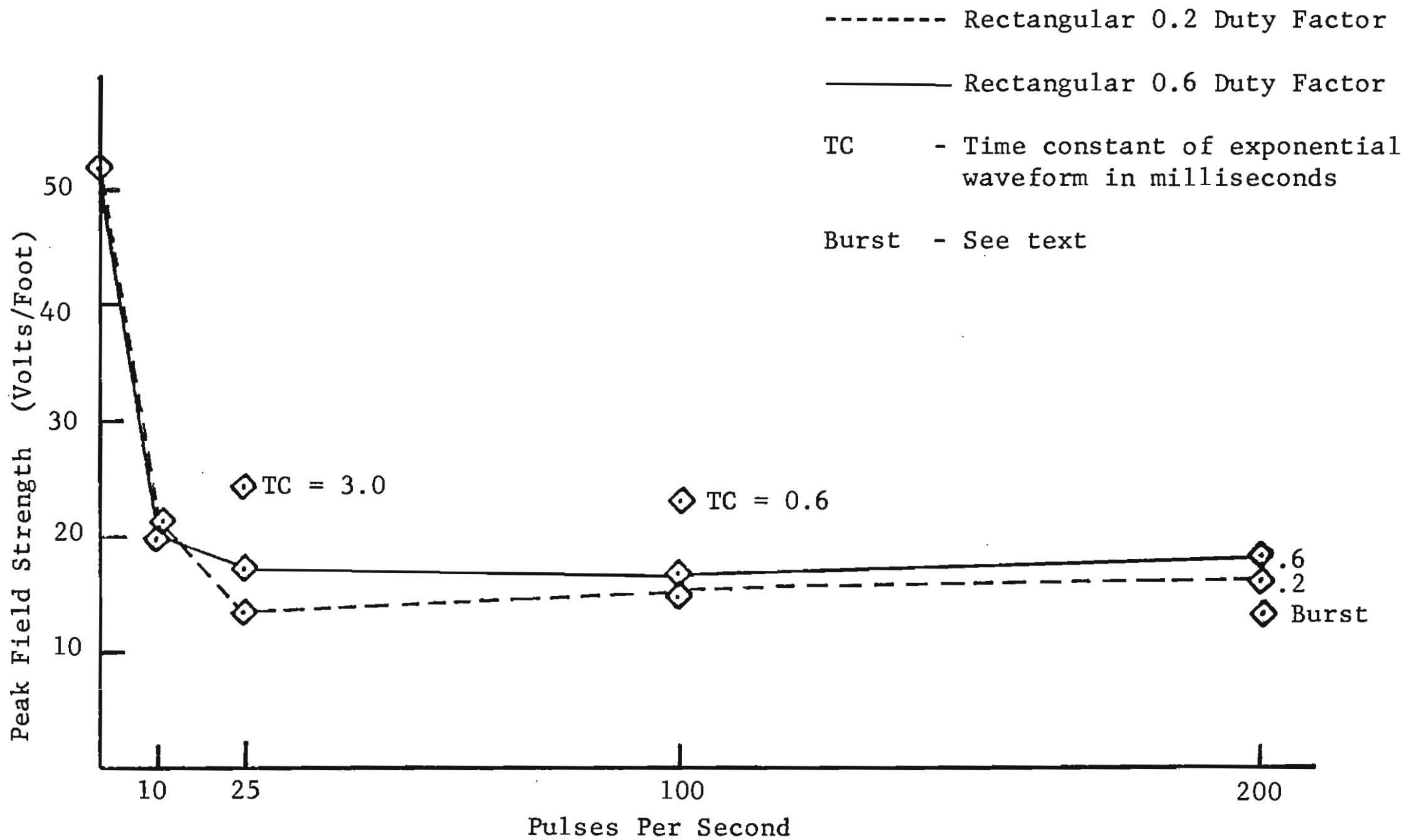


Figure 11. Field strength required to produce 75% immediate paralysis (within 10 seconds) for Bluegill I of average length 6" using various waveforms.

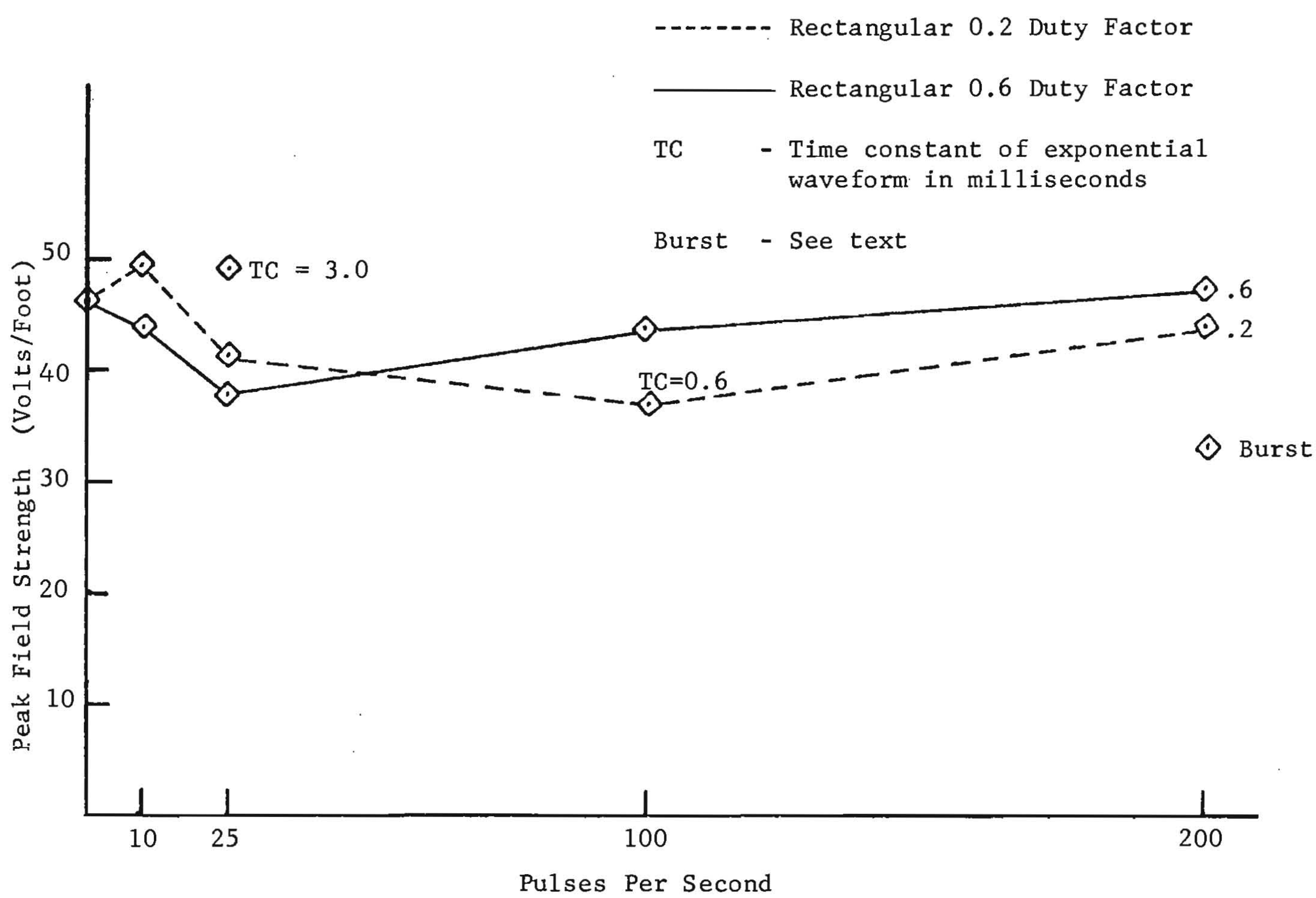


Figure 12. Field strength required to produce 75% immediate paralysis (within 10 seconds) for Bluegill II of average length 2" using various waveforms.

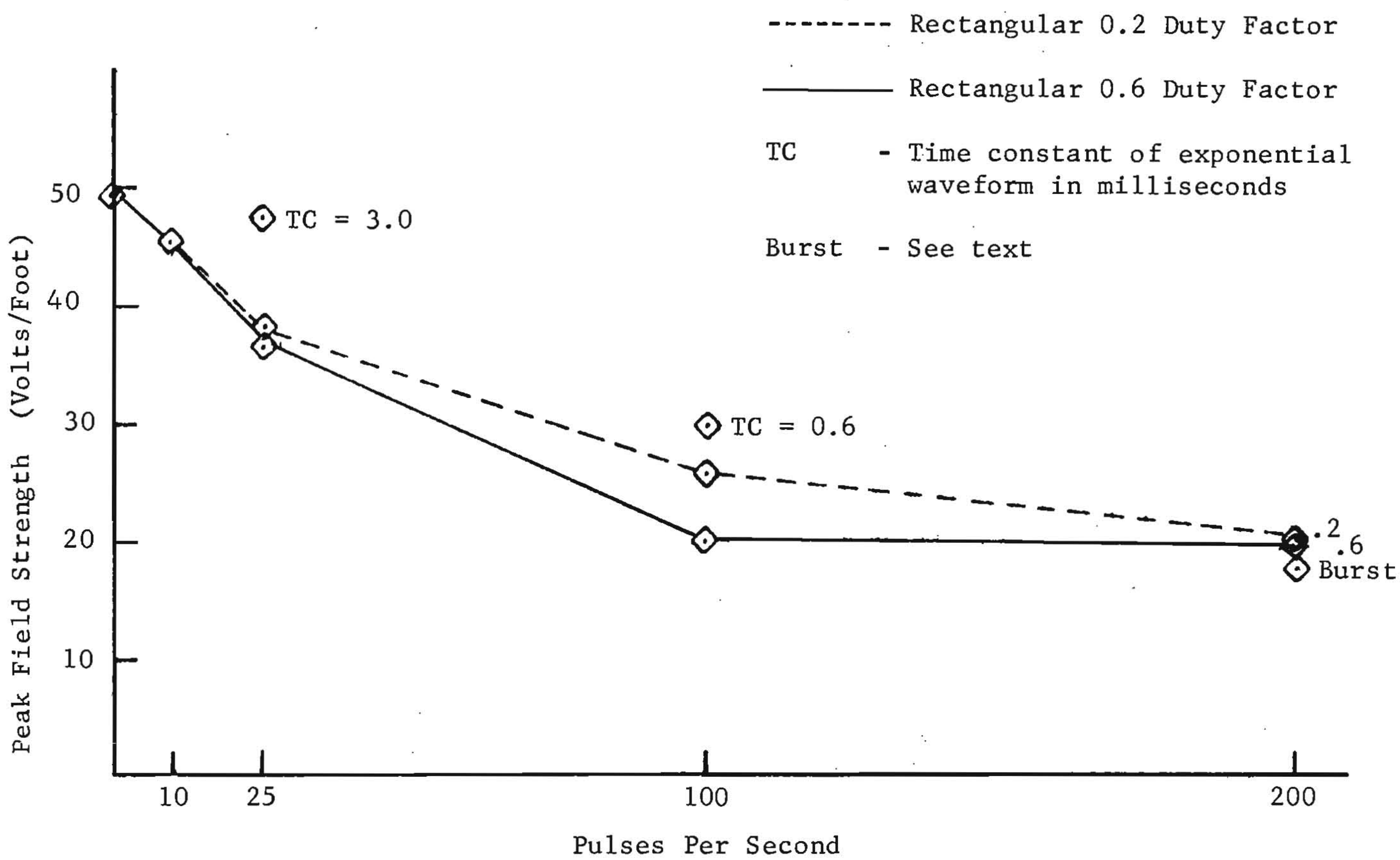


Figure 13. Field strength required to produce 75% immediate paralysis (within 10 seconds) for Largemouth Bass of average length 3.5" using various waveforms.

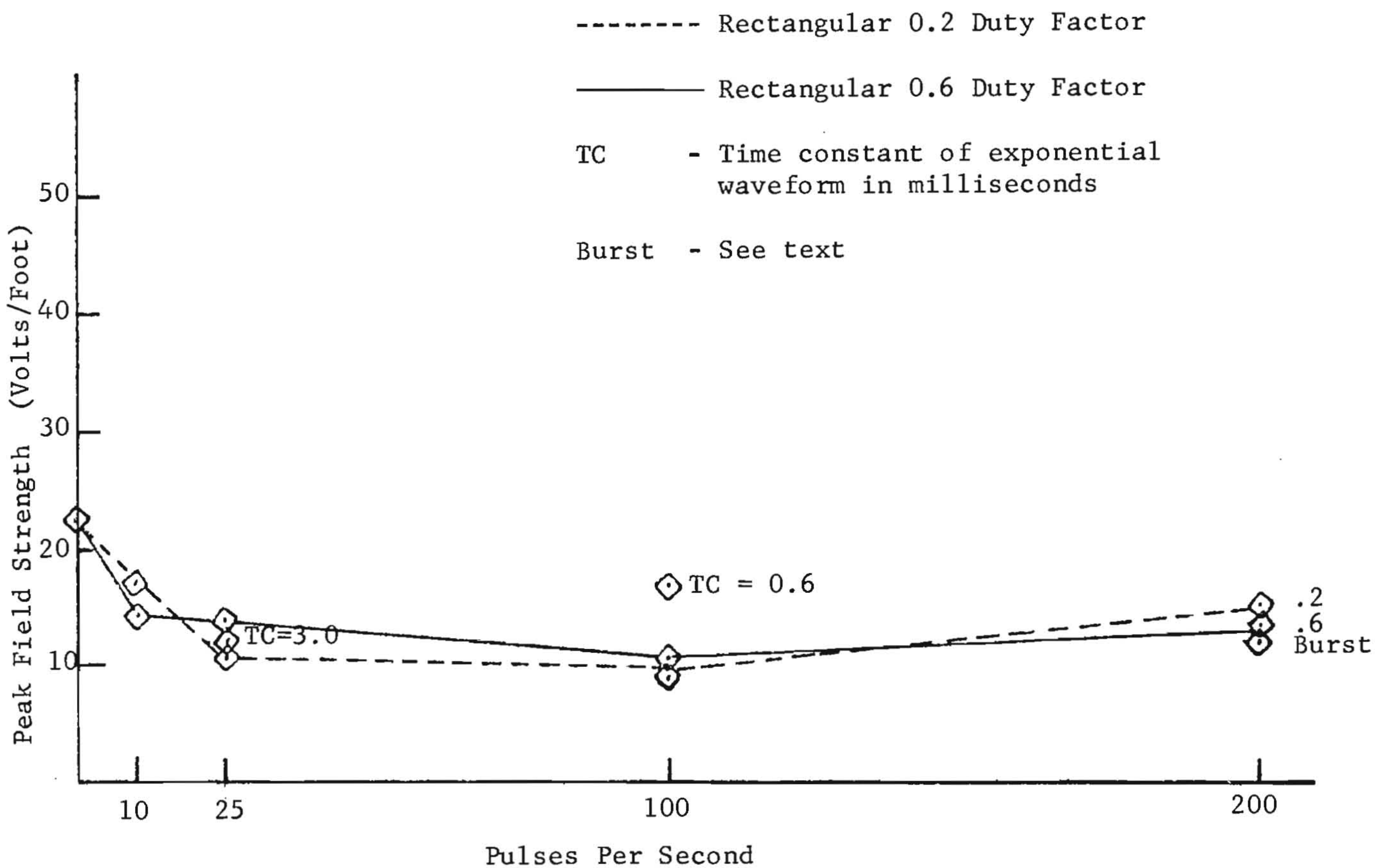


Figure 14. Field strength required to produce 75% immediate paralysis (within 10 seconds) for Bowfin of average length 16" using various waveforms.

second (PPS) and only about 17 to 18 volts/foot were required at frequencies of 25, 100, and 200 PPS. These data then indicate that 6" bluegill are more readily paralyzed at the frequencies 25, 100, and 200 PPS than at 10 PPS or at dc since, at the higher frequencies, a lower field strength was sufficient paralyze 3 fish in 4. It is also important to note that with a duty factor of 0.2, the field strength required was slightly lower than with a duty factor of 0.6 at most frequencies tested. If judged on the basis of peak field strength, the shorter rectangular pulses were usually slightly more effective than the longer pulses.

Figures 9, 10, 12, 13 and 14 show generally the same results for the other five groups of fish. The higher frequencies appear to be more effective than dc and 10 PPS, but most of the graphs show little change in response for frequencies above 25 PPS. The shorter pulses are in most cases slightly more effective than the longer.

These data were gathered using frequencies of dc, 10, 25, 100, and 200 PPS. Line segments drawn between the data points are not intended to indicate that responses to intermediate frequencies must lie on these lines. They were drawn for clarity so that general trends in the data might be more easily recognized.

Selectivity

A comparison of Figures 11 and 12 shows that with dc, about the same field strength is required to immobilize 2-inch bluegill as 6-inch bluegill. However, with the pulsed waveforms, a much stronger field is required to paralyze the smaller fish than the larger ones: 38 volts/foot or more compared with less than 20 volts/foot.

Figures 9 and 10 show somewhat the same tendencies for the catfish at the higher frequencies. The differences for this species are not so striking because the difference in the average sizes of the two groups of catfish is not nearly so great as for the bluegill. Still, it is evident that at the high frequencies, a greater field strength is required to paralyze the smaller fish. This conclusion is in agreement with the findings of other workers [1,5].

Data on the responses to exponential and burst waveforms are also presented on Figures 9 through 14. In terms of peak field strength, the exponential waveforms (25 PPS with 3.0 millisecond time constant and 100 PPS with 0.6 millisecond time constant) appear to be somewhat less effective than the rectangular pulses. However, the burst waveform appears to be somewhat more effective. The burst data has been placed on the figures at the frequency 200 PPS since the waveform is basically a 200 PPS (0.2 duty factor) pulse train from which 3 of every 8 pulses have been omitted. It may seem surprising that if 3 pulses in 8 are omitted, the effectiveness of the 200 PPS pulse train is increased, but the data consistently show this to be the case.

From these data it is difficult to make a direct comparison of the variations in susceptibility of different species because the fish which were tested were not only of different species but also were of different sizes, and size affects susceptibility. It would have been desirable to compare the responses of catfish, bluegill, bass and bowfin of the same size to determine any differences due to species. However, it was not possible to obtain similarly sized samples.

If the field strength (in volts/foot) is multiplied by a fish's length (in feet) the product is the head-to-tail voltage which it experiences, if it is assumed that the fish is aligned with the direction of flow of electric current in the water and that the field is not disturbed by the fish's presence. The data of Figures 9 through 14 are presented again in Figures 15 through 20 in terms of average head-to-tail potential instead of field strength. It appears, from the data on the two groups of catfish and the two groups of bluegill, that the voltage which had to be applied from head to tail in order to produce paralysis was not as strongly dependent on length at the higher frequencies as at the lower frequencies. Comparing Figure 15 with 16 and 17 with 18, it is evident that at the higher frequencies about 12 to 16 volts head-to-tail paralyzed three fourths of the 8-to 11-inch catfish population and 7 to 9 volts head-to-tail paralyzed three-fourths of the 2-to 6-inch bluegill.

In order to facilitate a further comparison of the differences of response of different species, the data are presented again with data for different species placed side by side in Figures 21 through 32. Each figure presents data for a different waveform. The first graph in each figure presents the data in terms of applied field strength whereas the second presents it in terms of head-to-tail voltage. It appears that the head-to-tail voltage required to paralyze catfish and bluegill is independent of the fish's length for rectangular pulses at 100 and 200 PPS and for the burst waveform. (See Figures 27, 28, 29, 30, and 22.) This independence of length appears not to extend to the lower frequencies or to the exponential pulses. The burst waveform appears to have produced the most nearly uniform response of the twelve waveforms tested in terms of average head-to-tail potential. (See Figure 22.) It might therefore be a preferable waveform if a minimum of

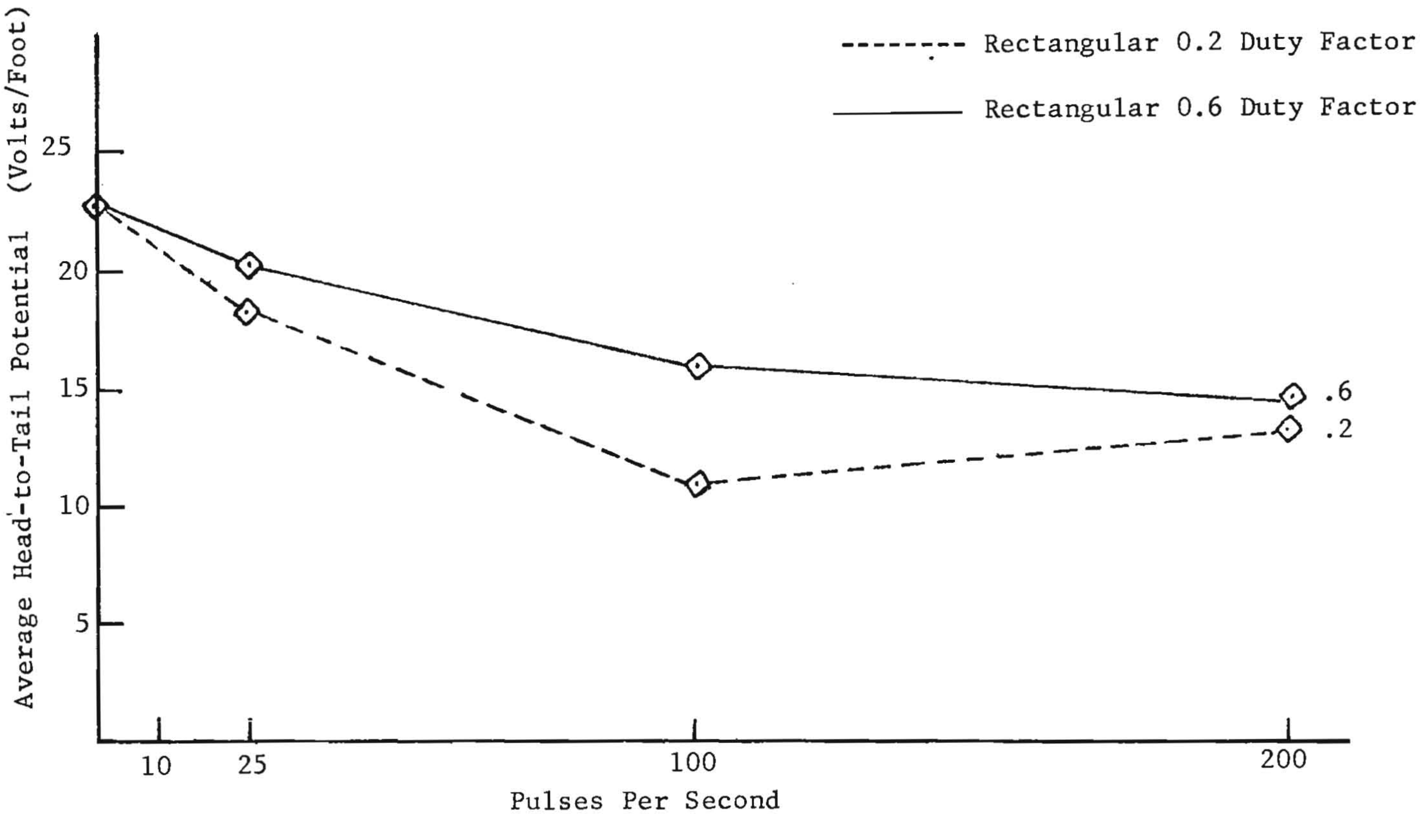


Figure 15. Average head-to-tail potential required to produce 75% paralysis (within 10 seconds) for Channel Catfish I of average length 11" using rectangular pulse trains.

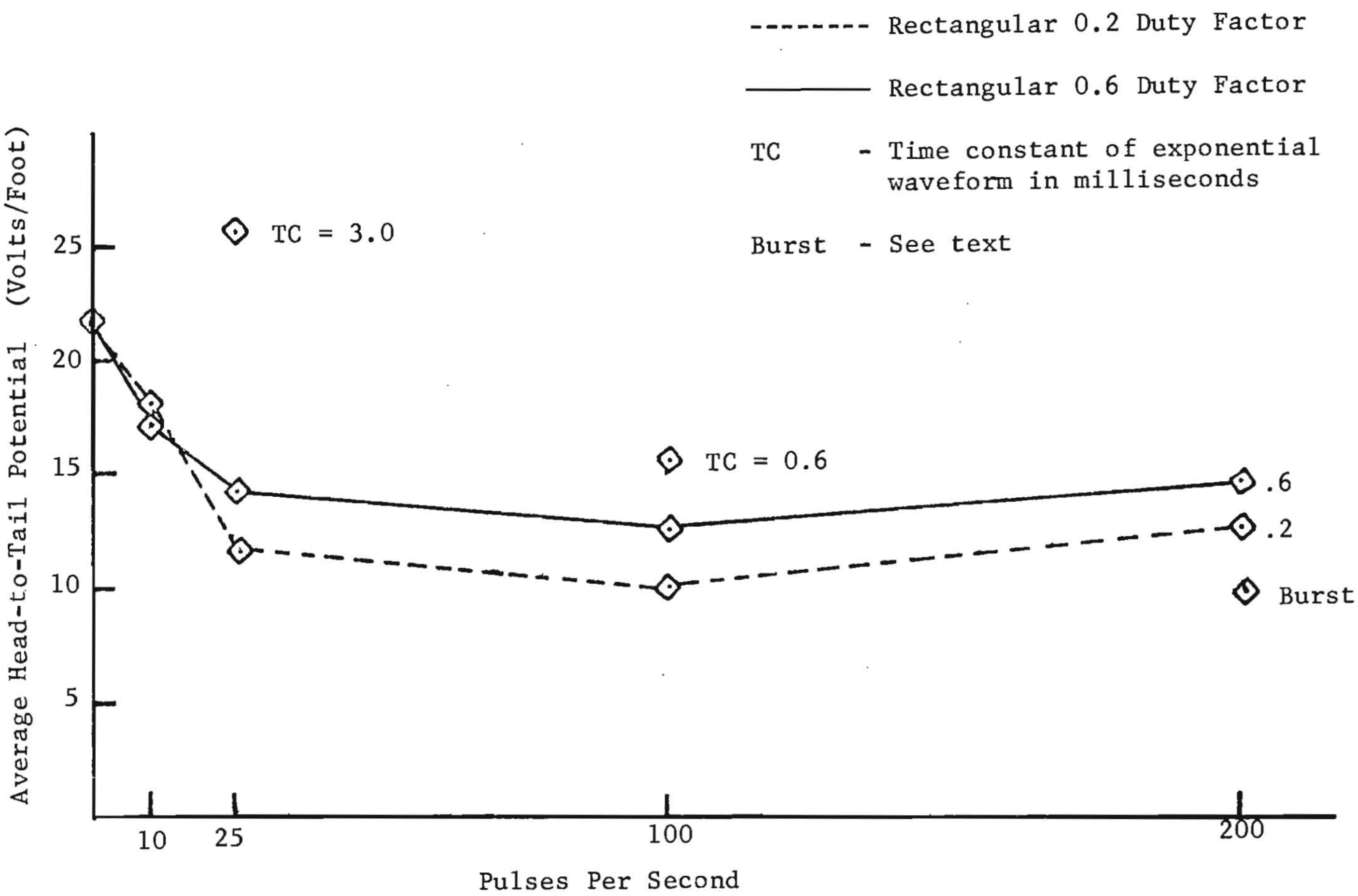


Figure 16. Average head-to-tail potential required to produce 75% paralysis (within 10 seconds) for Channel Catfish II of average length 8.5" using various waveforms.

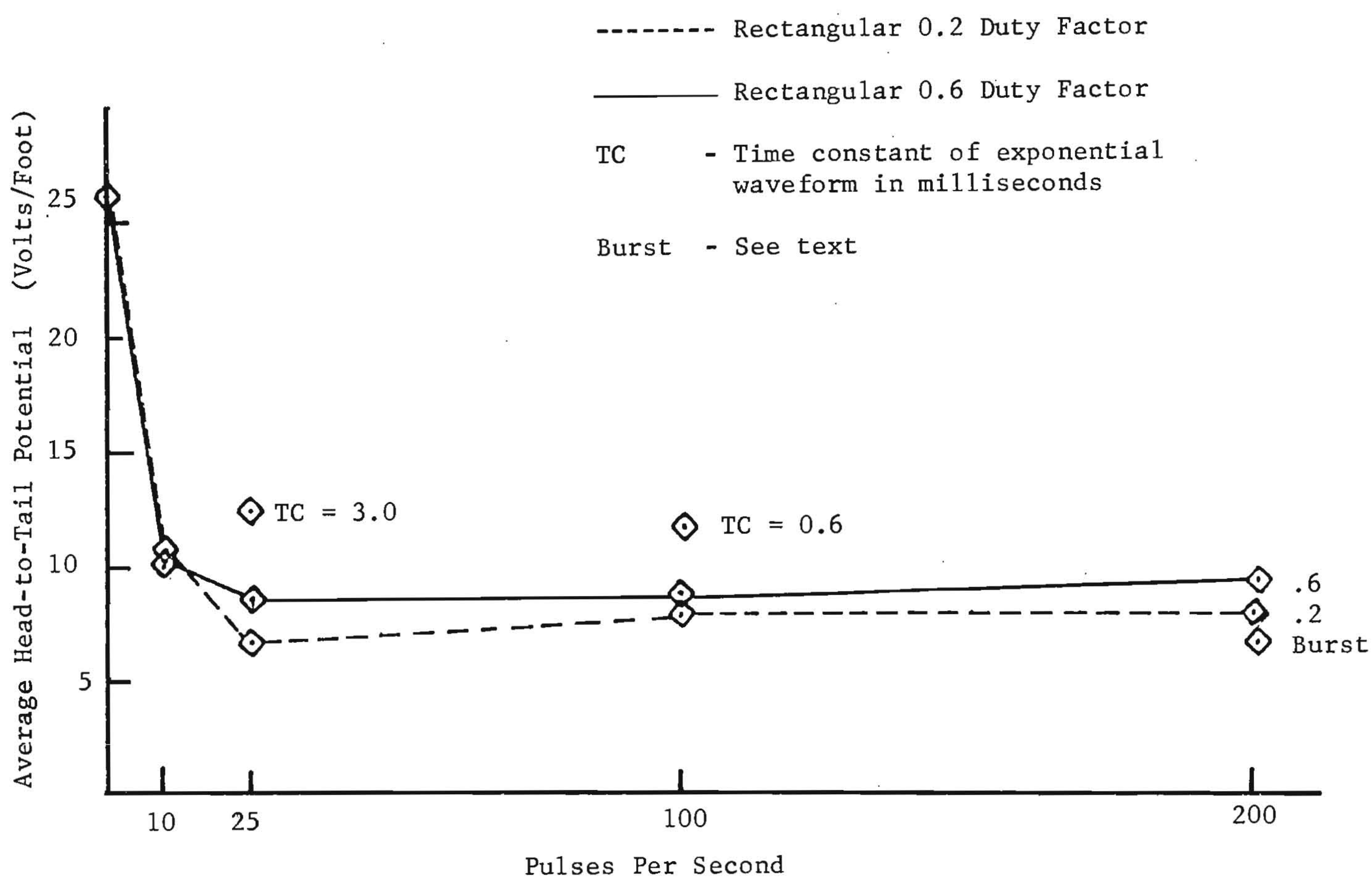


Figure 17. Average head-to-tail potential required to produce 75% paralysis (within 10 seconds) for Bluegill I of average length 6" using various waveforms.

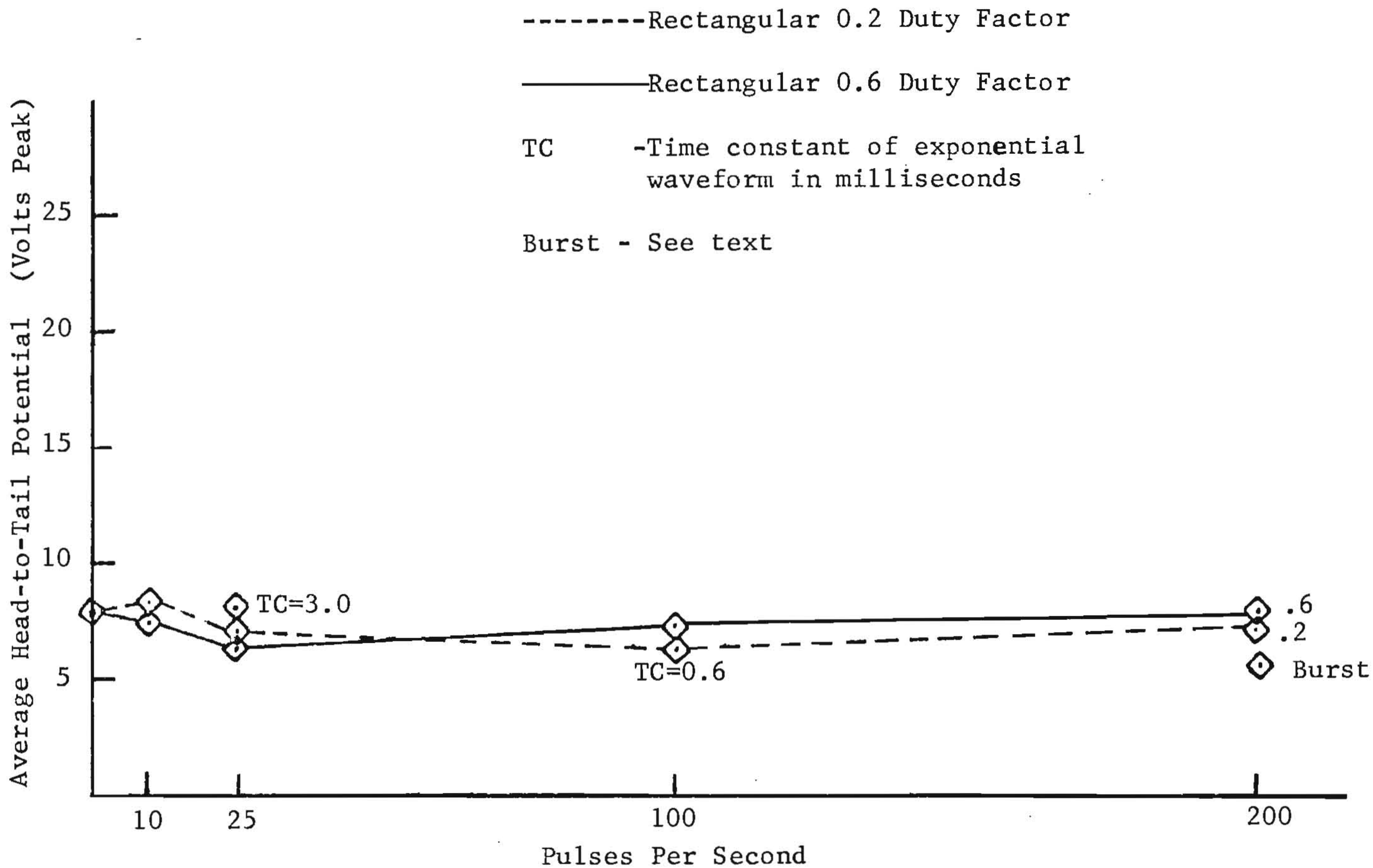


Figure 18. Average head-to-tail potential required to produce 75% paralysis (within 10 seconds) for Bluegill II of average length 2" using various waveforms.

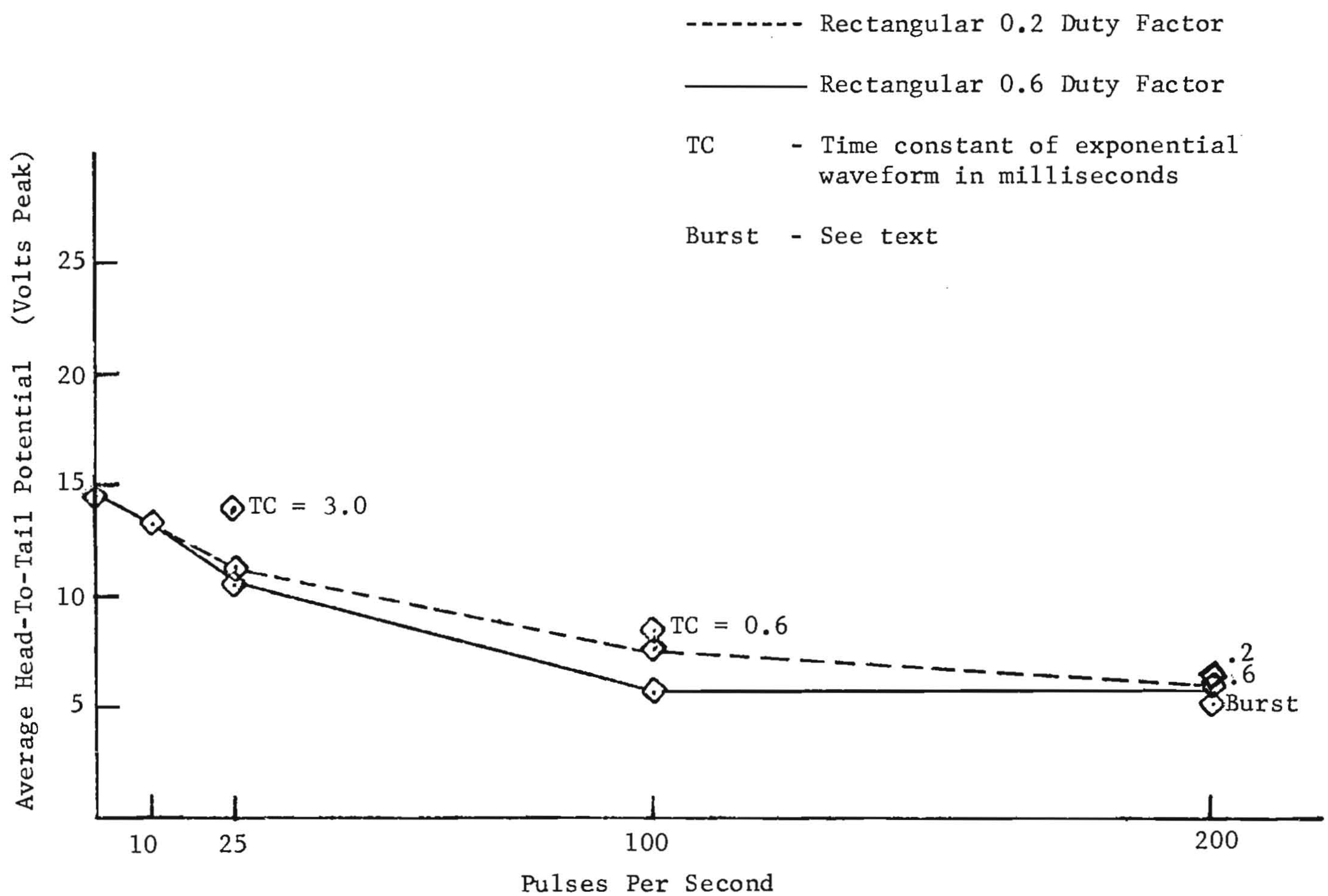


Figure 19. Average head-to-tail potential required to produce 75% paralysis (within 10 seconds) for Largemouth Bass of average length 3.5" using various waveforms.

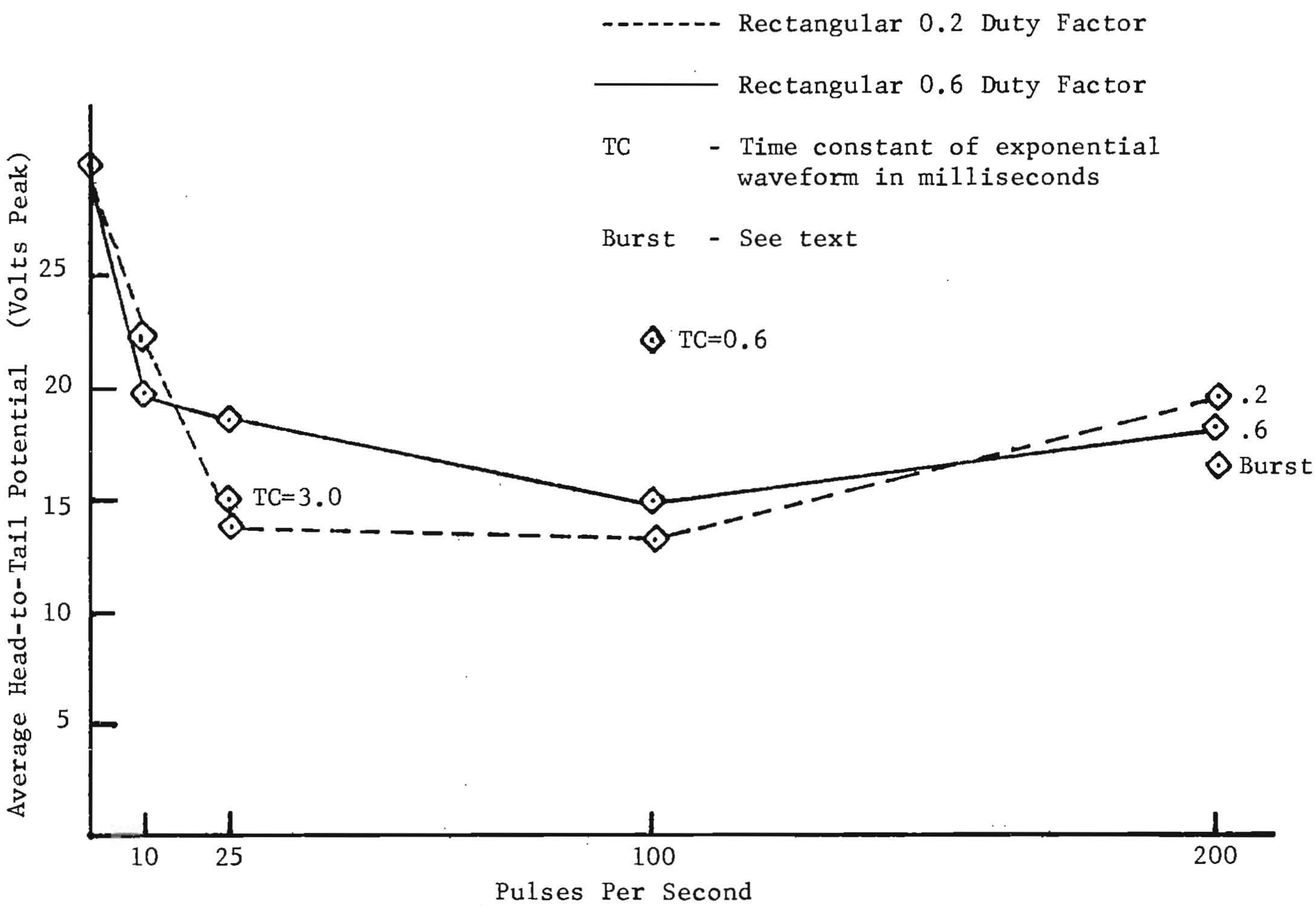


Figure 20. Average head-to-tail potential required to produce 75% paralysis (within 10 seconds) for Bowfin of average length 16" using various waveforms.

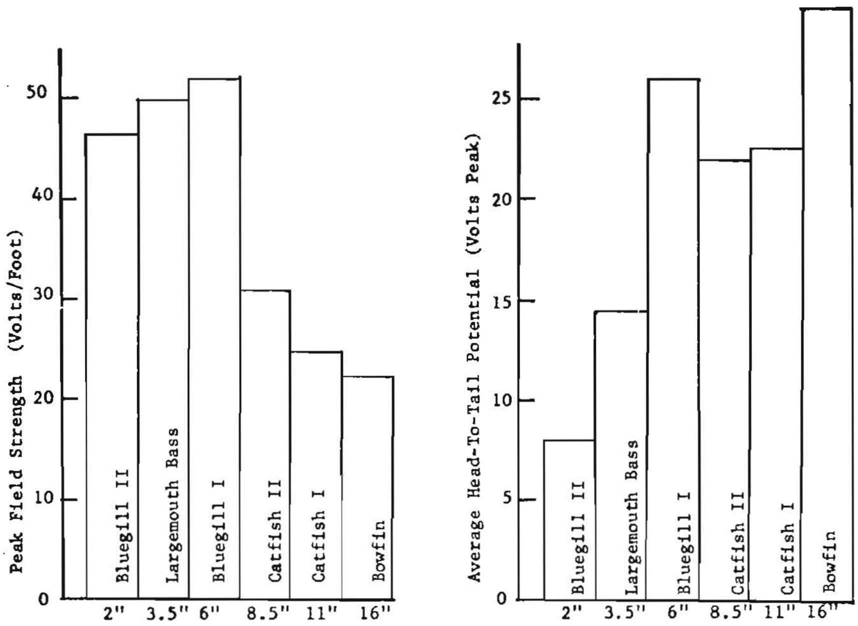


Figure 21. Field strength and average head-to-tail potential required to produce 75% immediate paralysis in each of the fish groups tested using a dc waveform. Average length of each group is indicated.

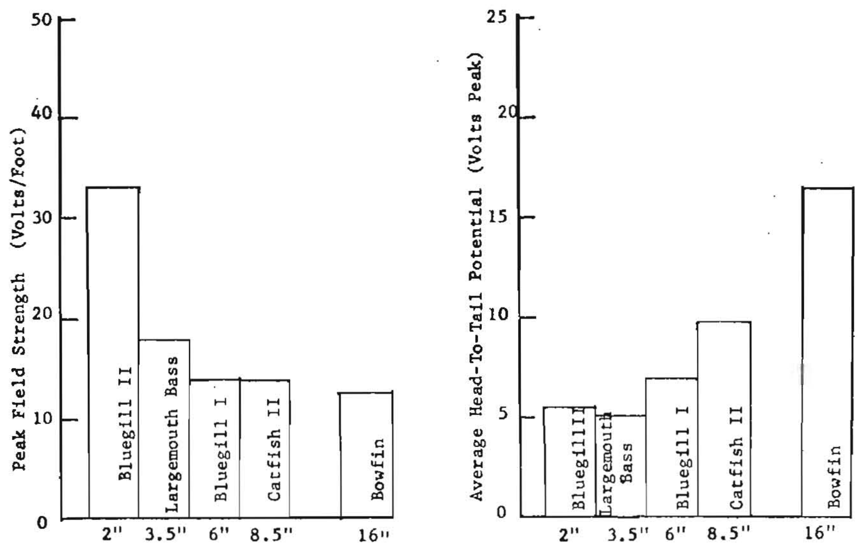


Figure 22. Field strength and average head-to-tail potential required to produce 75% immediate paralysis in each of the fish groups tested using a burst waveform. Average length of each group is indicated.

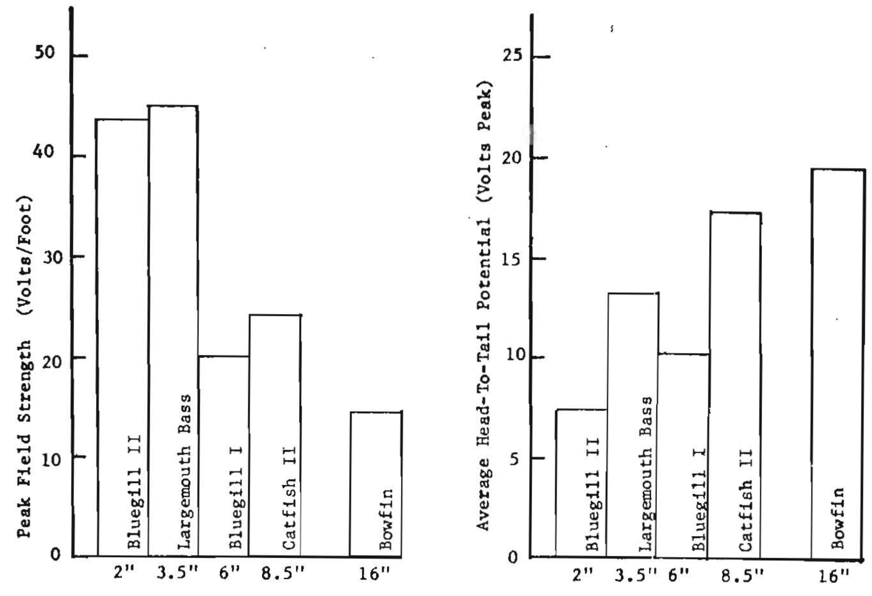


Figure 23. Field strength and average head-to-tail potential required to produce 75% immediate paralysis in each of the fish groups tested using a 10 PPS rectangular waveform of 0.6 duty factor. Average length of each group is indicated.

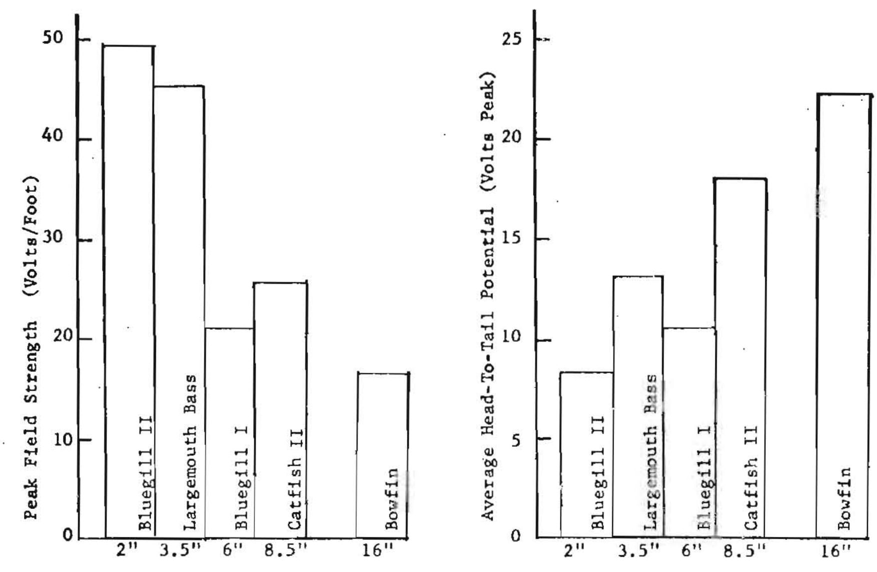


Figure 24. Field strength and average head-to-tail potential required to produce 75% immediate paralysis in each of the fish groups tested using a 10 PPS rectangular waveform of 0.2 duty factor. Average length of each group is indicated.

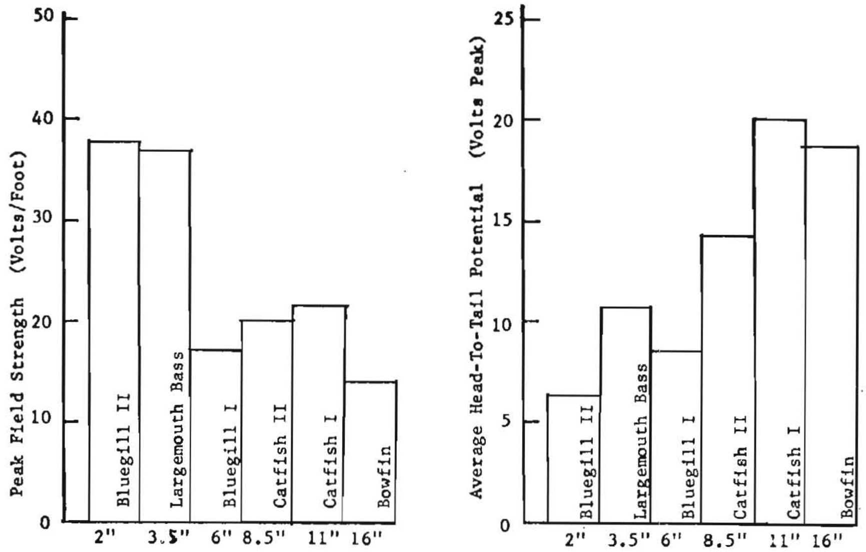


Figure 25. Field strength and average head-to-tail potential required to produce 75% immediate paralysis in each of the fish groups tested using a 25 PPS rectangular waveform of 0.6 duty factor. Average length of each group is indicated.

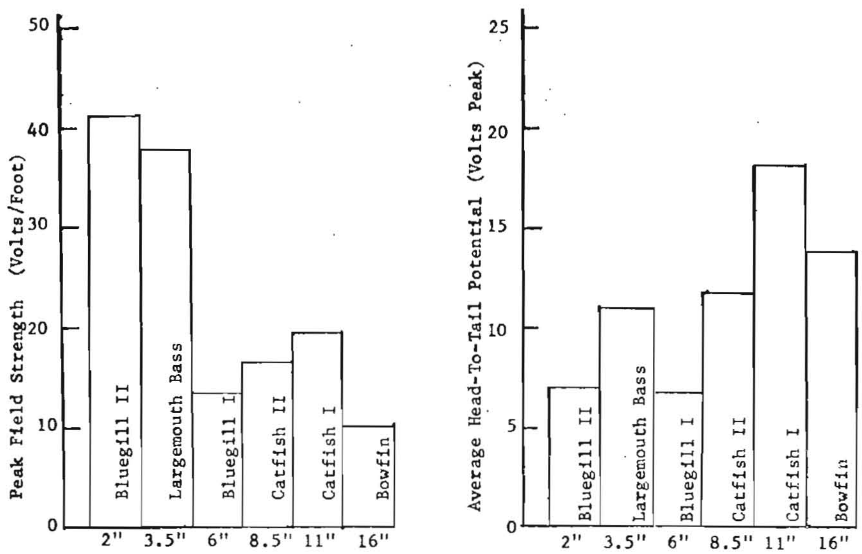


Figure 26. Field strength and average head-to-tail potential required to produce 75% immediate paralysis in each of the fish groups tested using a 25 PPS rectangular waveform of 0.2 duty factor. Average length of each group is indicated.

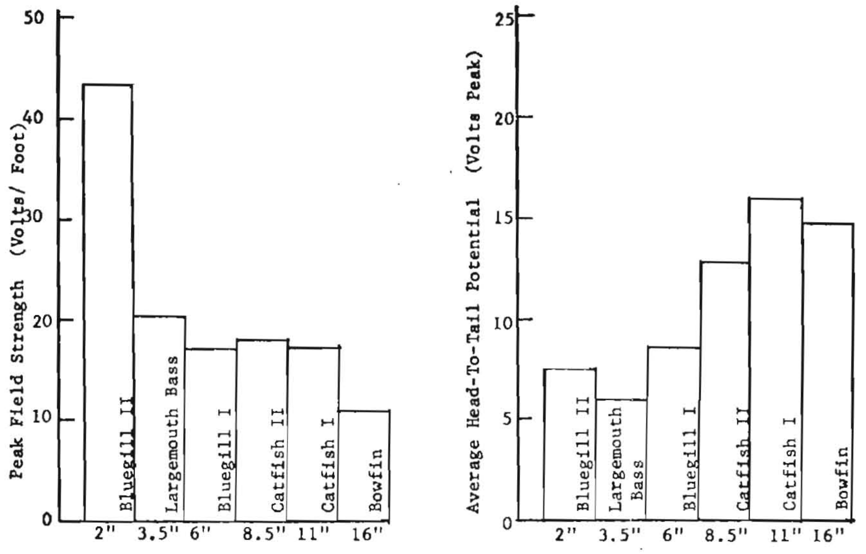


Figure 27. Field strength and average head-to-tail potential required to produce 75% immediate paralysis in each of the fish groups tested using a 100 PPS rectangular waveform of 0.6 duty factor. Average length of each group is indicated.

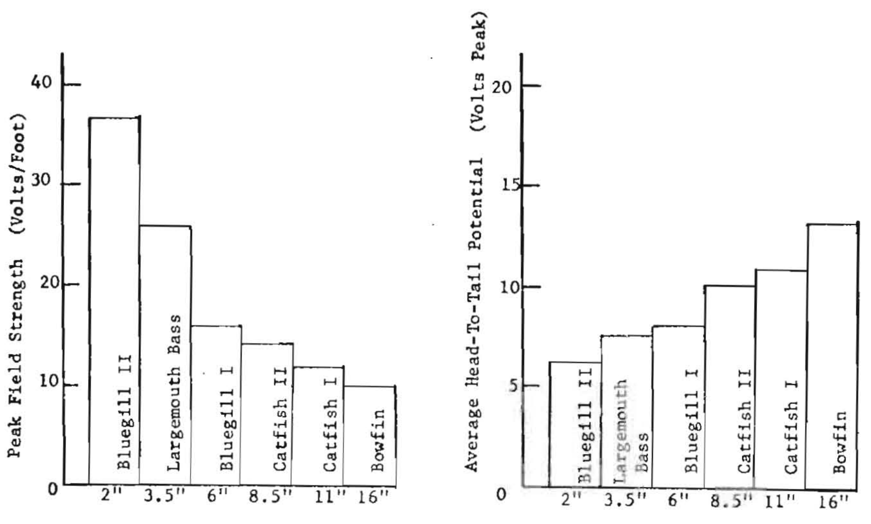


Figure 28. Field strength and average head-to-tail potential required to produce 75% immediate paralysis in each of the fish groups tested using a 100 PPS rectangular waveform of 0.2 duty factor. Average length of each group is indicated.

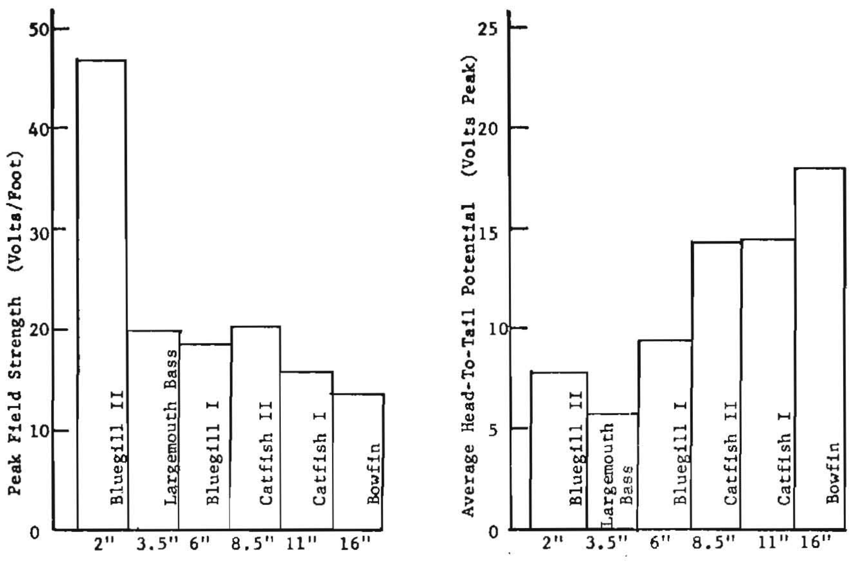


Figure 29. Field strength and average head-to-tail potential required to produce 75% immediate paralysis in each of the fish groups tested using a 200 PPS rectangular waveform of 0.6 duty factor. Average length of each group is indicated.

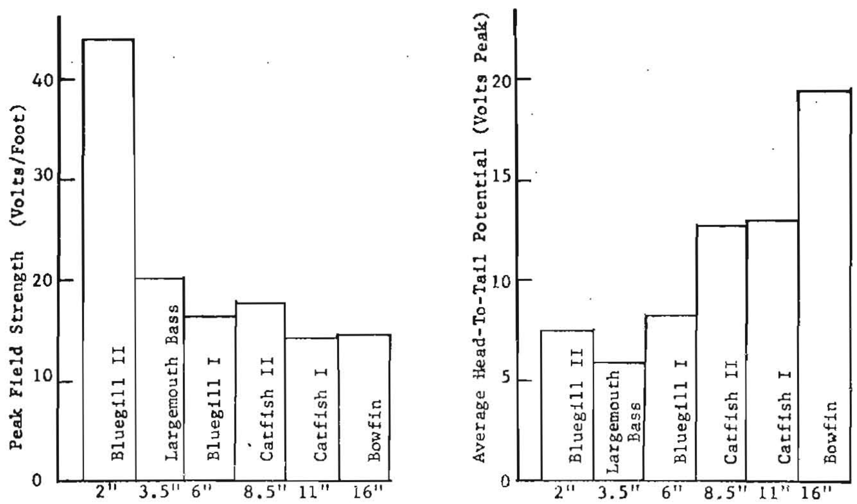


Figure 30. Field strength and average head-to-tail potential required to produce 75% immediate paralysis in each of the fish groups tested using a 200 PPS rectangular waveform of 0.2 duty factor. Average length of each group is indicated.

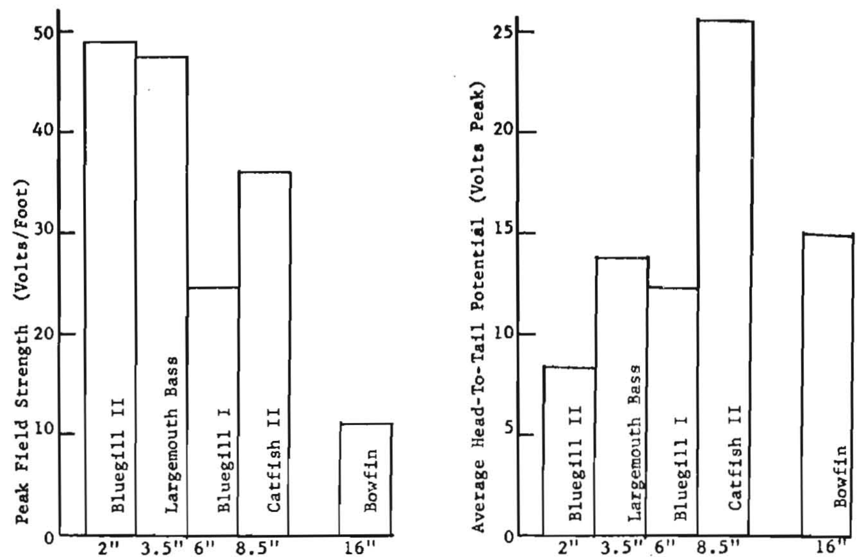


Figure 31. Field strength and average head-to-tail potential required to produce 75% immediate paralysis in each of the fish groups tested using a 25 PPS exponential waveform of 3.0 millisecond time constant. Average length of each group is indicated.

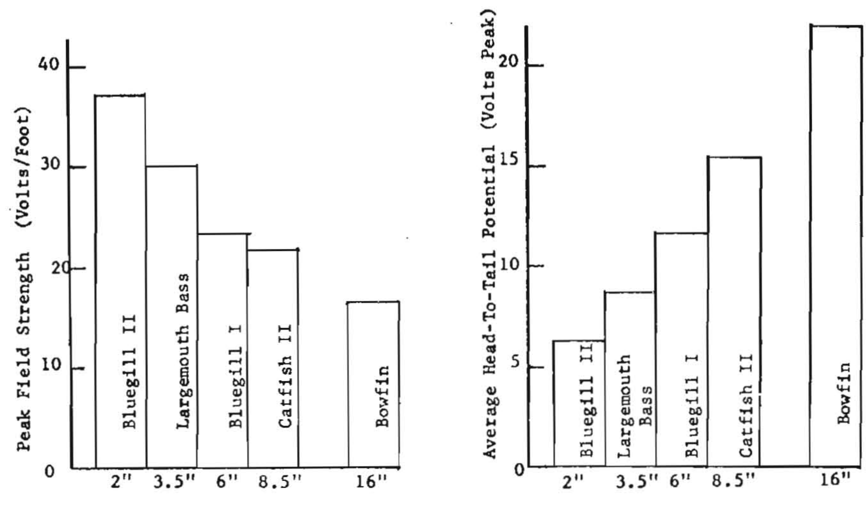


Figure 32. Field strength and average head-to-tail potential required to produce 75% immediate paralysis in each of the fish groups tested using a 100 PPS exponential waveform of 0.6 millisecond time constant. Average length of each group is indicated.

selectivity with regard to species were desired.

In attempting to determine the effect of size on a fish's reaction, it is perhaps risky to compare fish of different species. However, since the fish which were tested were of different sizes, it seemed wise to take advantage of that fact to see if any general trends could be detected. Paralysis data for all six groups of fish have been plotted against frequency (for rectangular pulses) and length (regardless of species) in the three-dimensional representations of Figure 33. Data for pulse trains having a duty factor of 0.6 are shown in the upper graph, 0.2 in the lower.

The same general trends are clear in both graphs. The fact that the slope generally rises toward the left indicates that the smaller fish require higher electric field strengths to cause paralysis. It is also clear that since the graph generally rises toward the rear, the lower frequencies are less effective, requiring higher field strengths to produce paralysis. These conclusions are not new but they can be drawn perhaps more easily from graphs such as those of Figure 33 in which a larger quantity of data is displayed and relationships between length and excitation frequency can be observed.

Figure 34 presents the same data in terms of head-to-tail potential, assuming as before that the fish were aligned along the direction of current flow and that their presence did not disturb the field configuration. The axes for length in the graphs of Figure 34 have been reversed from the previous figure so that a clearer view of the surface could be obtained. The smallest sizes appear to require less head-to-tail potential for paralysis than the large fish, especially at low frequencies. It appears from the rise toward the rear of the graphs that except for the smallest fish, the low frequencies

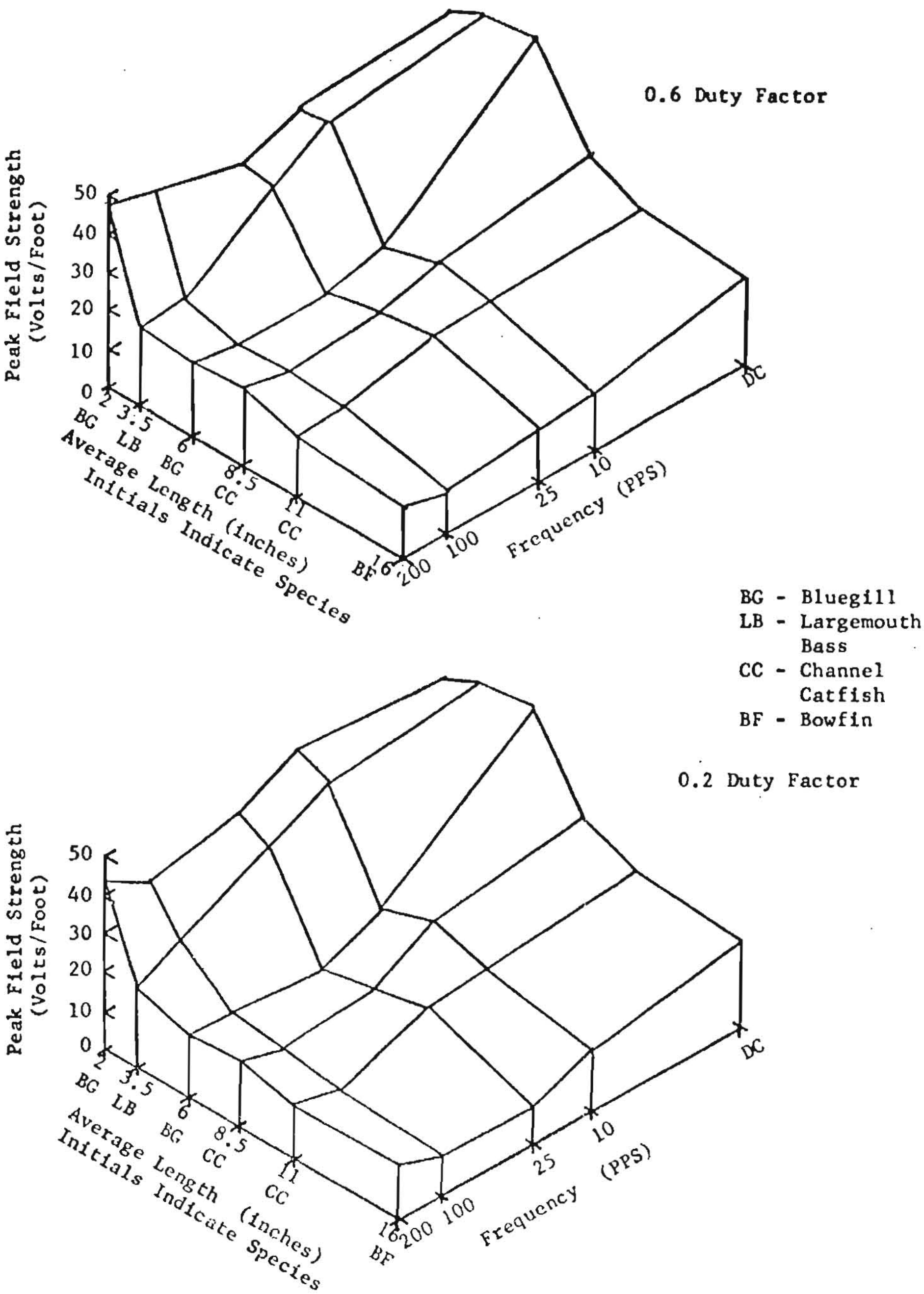


Figure 33. Field strength versus frequency with each species placed according to average length for rectangular pulse trains having duty factors of 0.6 and 0.2.

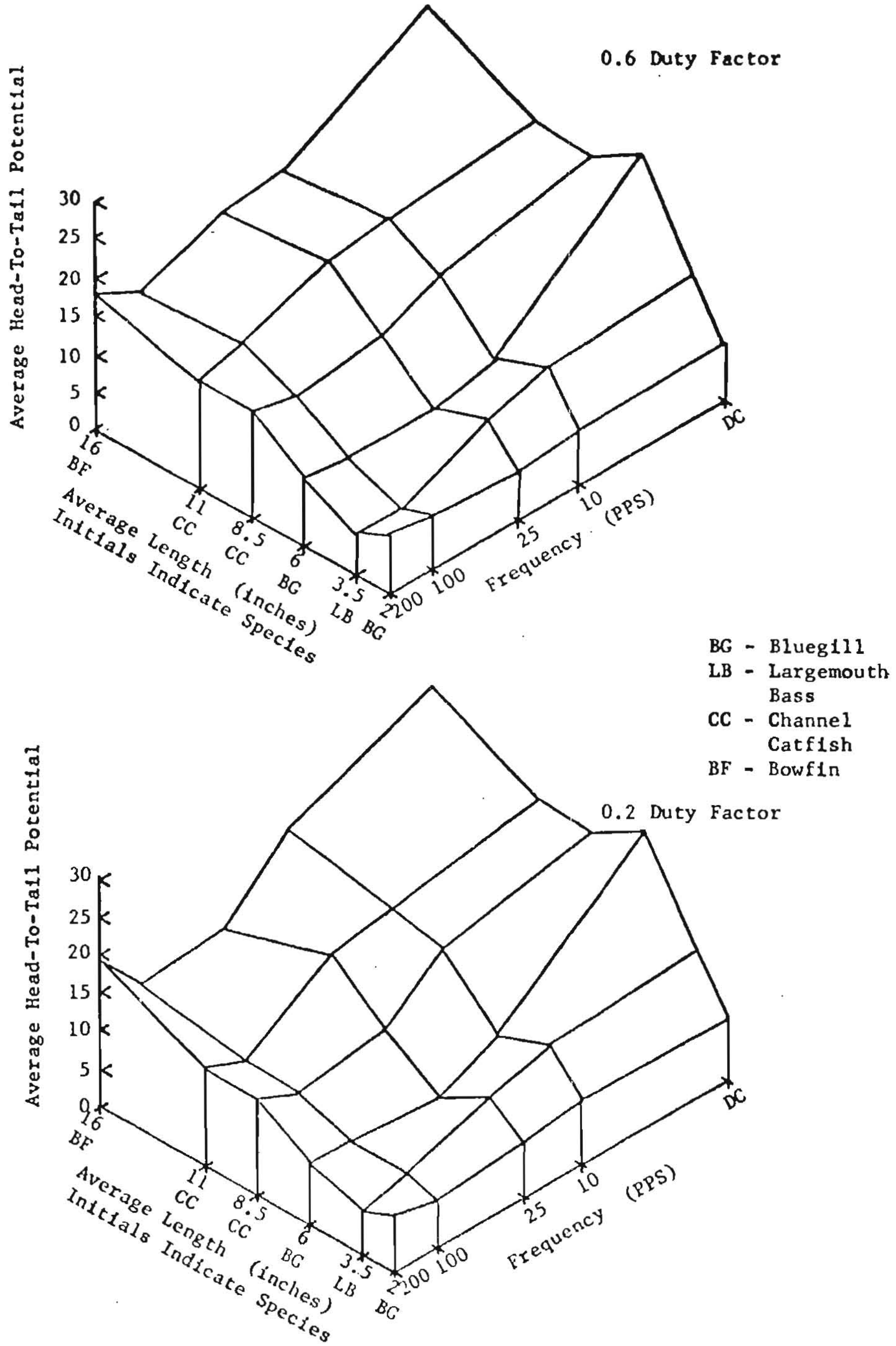


Figure 34. Average head-to-tail potential versus frequency with each species placed according to average length for rectangular pulse trains having duty factors of 0.6 and 0.2.

required larger head-to-tail potentials to cause paralysis than the higher frequencies.

If, in a field situation, one wished to collect a certain category of fish (based on species and size) but to ignore another, it would be helpful to know how large a field strength is required to paralyze all of the desired category and how small the field strength would have to be in order not to paralyze any in the unwanted category. Such information is not available from the foregoing figures, but Figures 35 through 46 are presented to indicate the degree of selectivity which might be possible. The graphs are based on the limited amount of data collected during this study and should be taken only as roughly approximate indicators of the expected behavior.

Of course, it is necessary to confine the conclusions to the six groups of fish which were tested. A separate page has been used for each of the electrical waveforms and a separate graph has been drawn for each group of fish tested. The vertical scales at the right indicate percent of fish paralyzed, from 0% to 100% for each group of fish. The horizontal scales at the top and bottom of each figure indicate field strength. The slanted lines on the graphs indicate the percentage paralyzed as a function of voltage. The top graph in Figure 35 indicates, for example, that for 2-inch bluegill shocked with dc, 100% will be paralyzed at a field strength of 49 volts per foot or more, about 50% will be paralyzed at 42 volts per foot, about 25% will be paralyzed at 39 volts per foot. This is what the measurements indicate, but the size of the test sample is not sufficiently large to allow great reliability to be placed in the accuracy of such numbers. The slanted lines have not been drawn below 25% because of the uncertainty in the data.

These graphs can be used to indicate which categories of fish might be

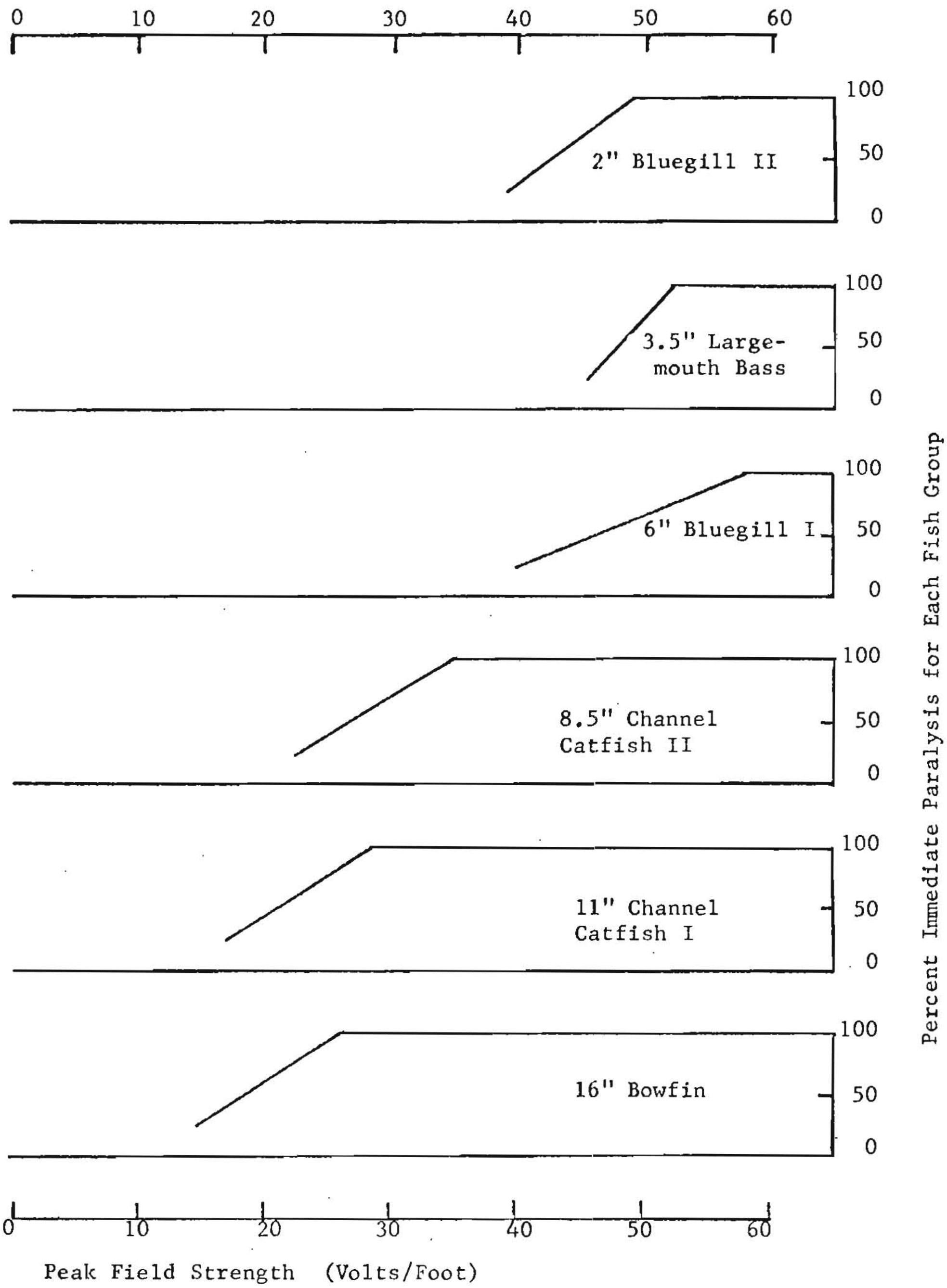


Figure 35. Percentage immediate paralysis versus applied field strength for each of the fish groups tested using dc.

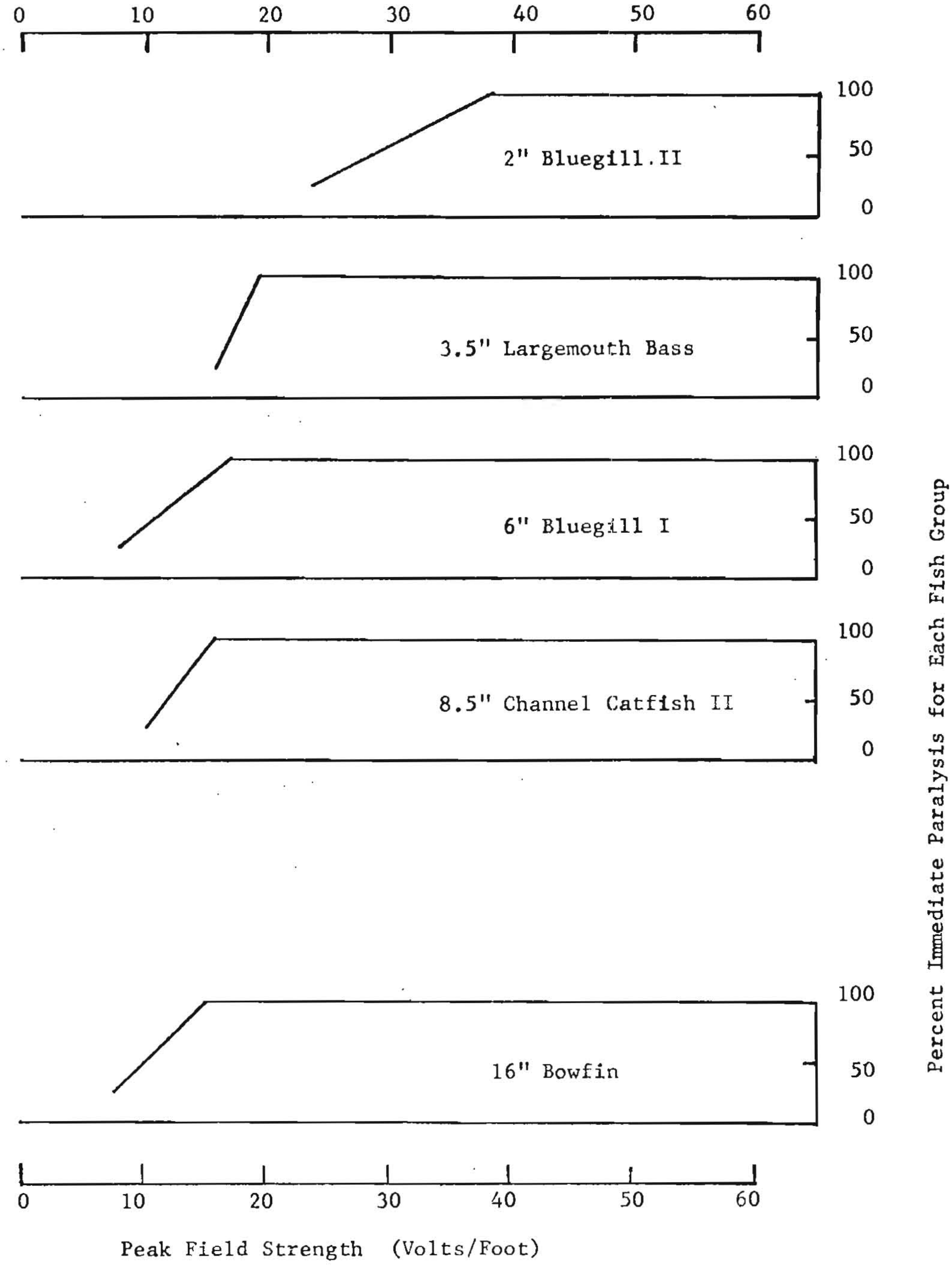


Figure 36. Percentage immediate paralysis versus applied field strength for each of the fish groups tested using a burst waveform.

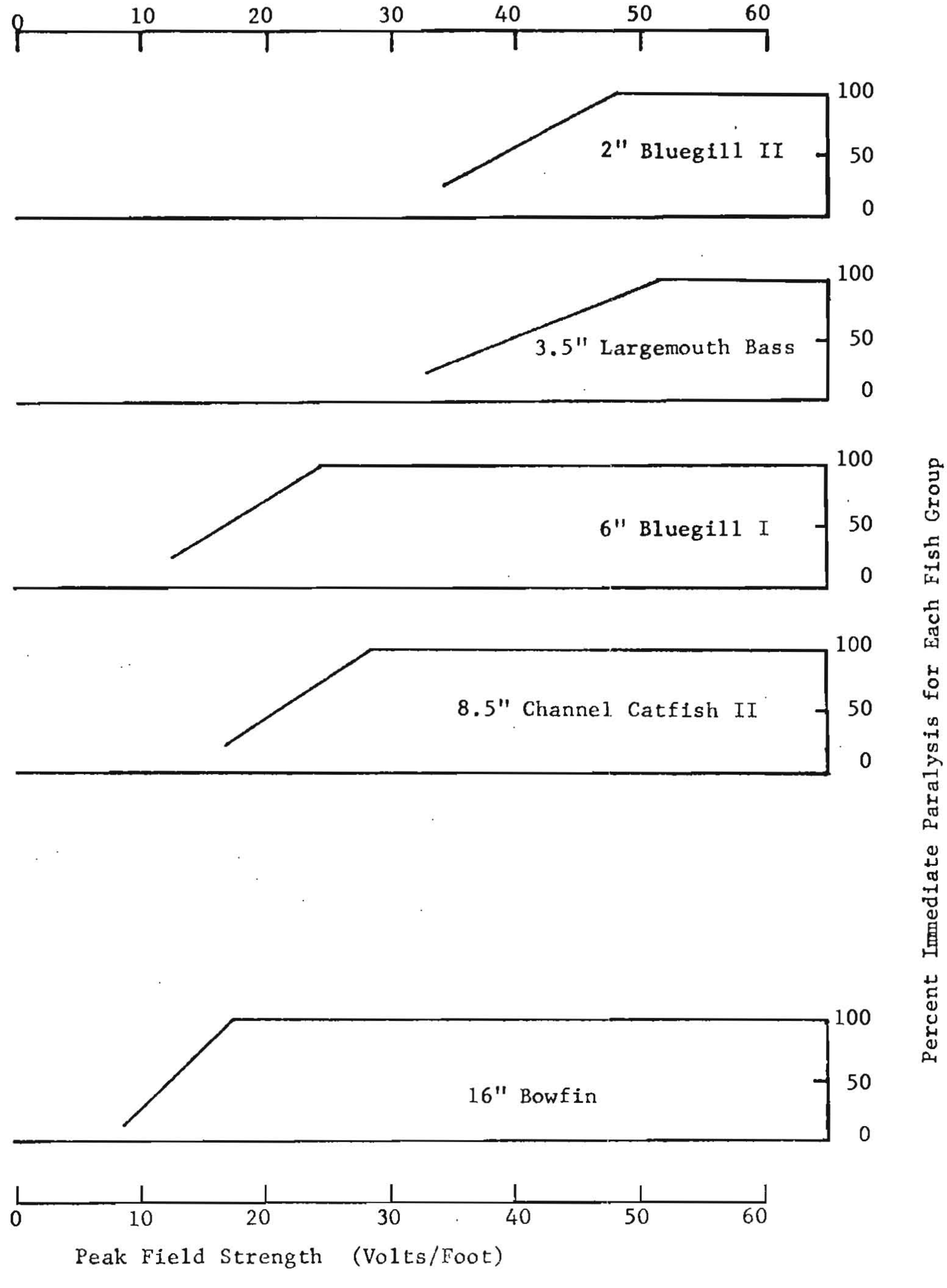


Figure 37. Percentage immediate paralysis versus applied field strength for each of the fish groups tested using a 10 PPS rectangular waveform of 0.6 duty factor.

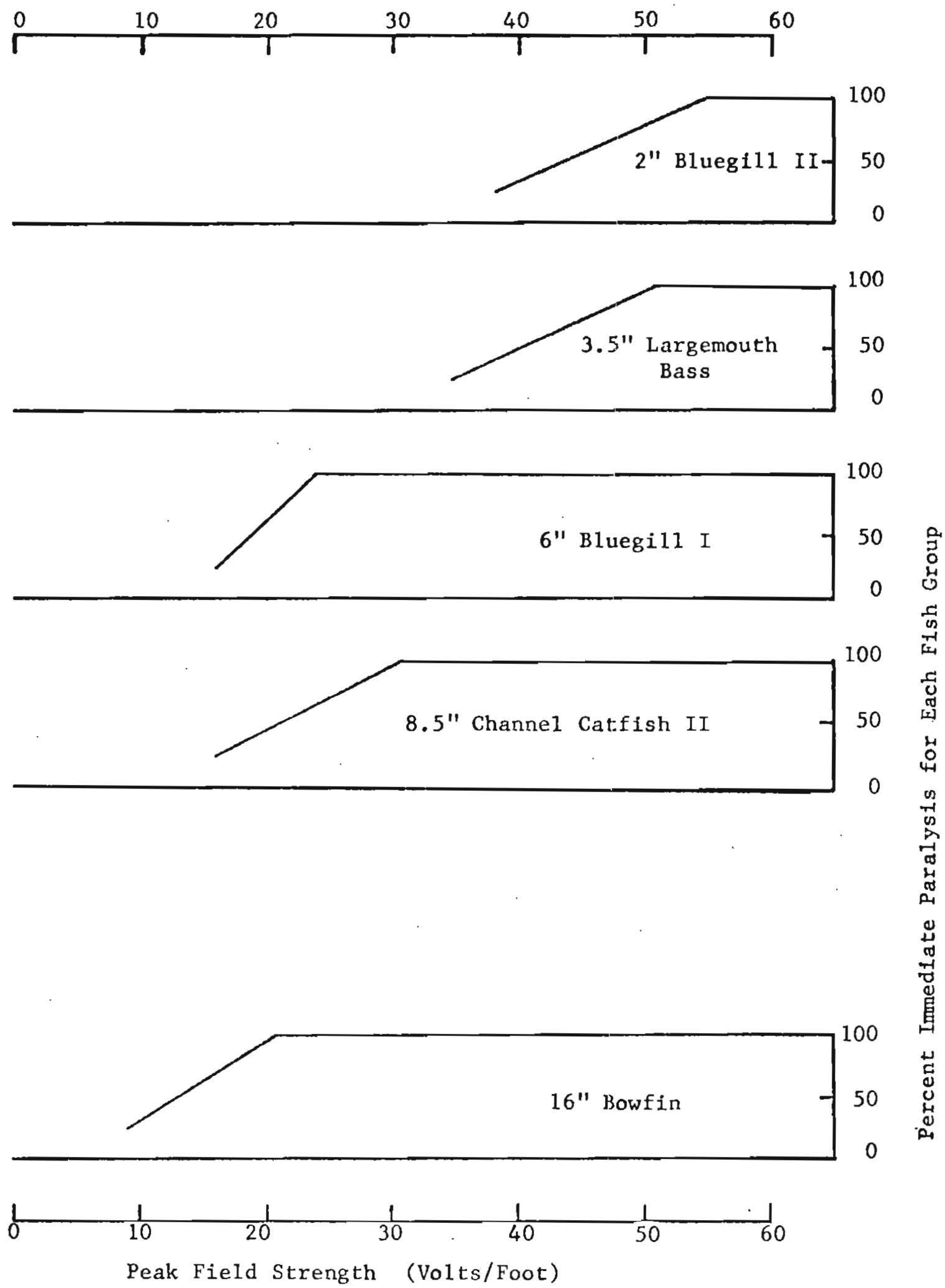


Figure 38. Percentage immediate paralysis versus applied field strength for each of the fish groups tested using a 10 PPS rectangular waveform of 0.2 duty factor.

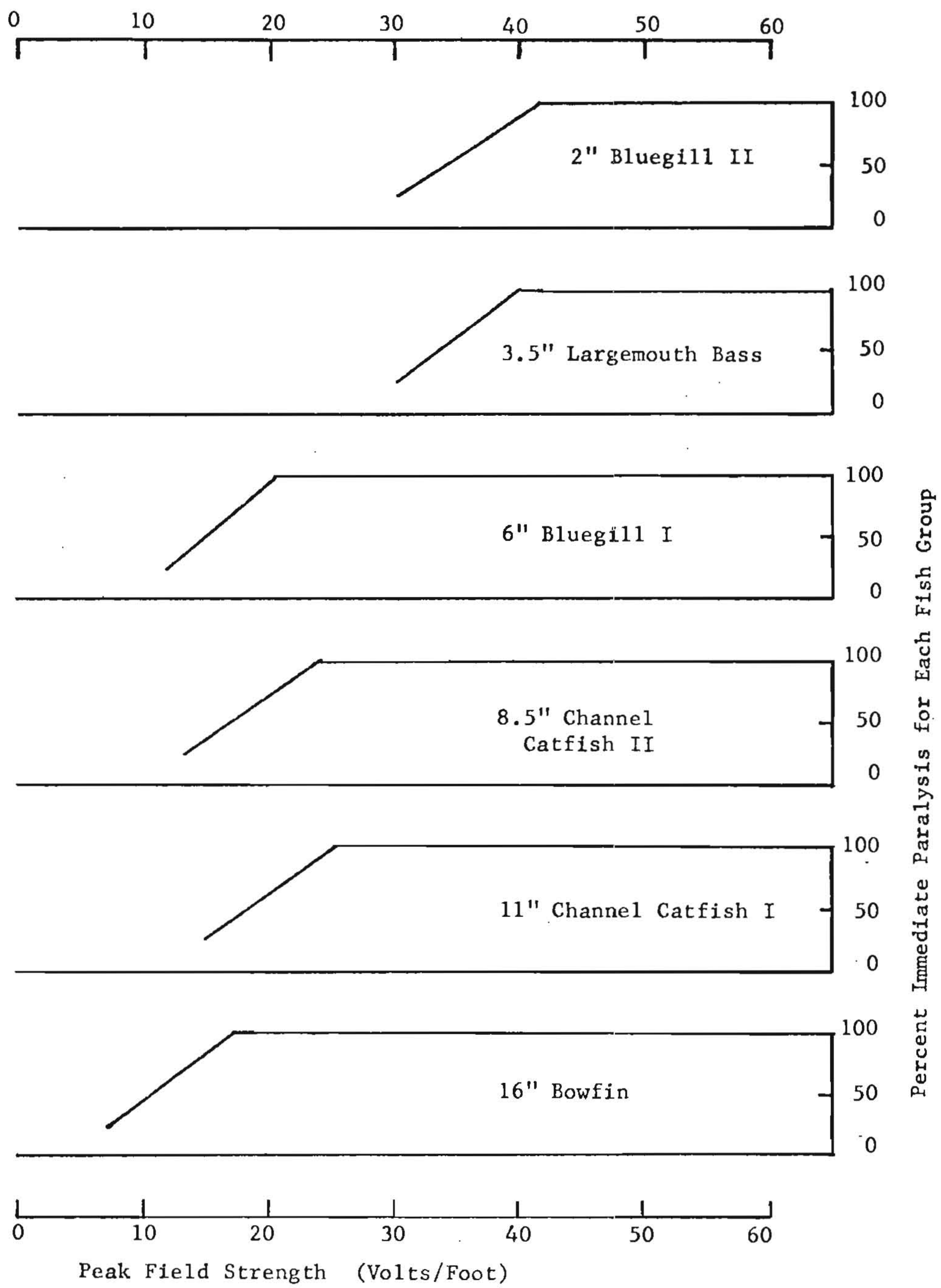


Figure 39. Percentage immediate paralysis versus applied field strength for each of the fish groups tested using a 25 PPS rectangular waveform of 0.6 duty factor.

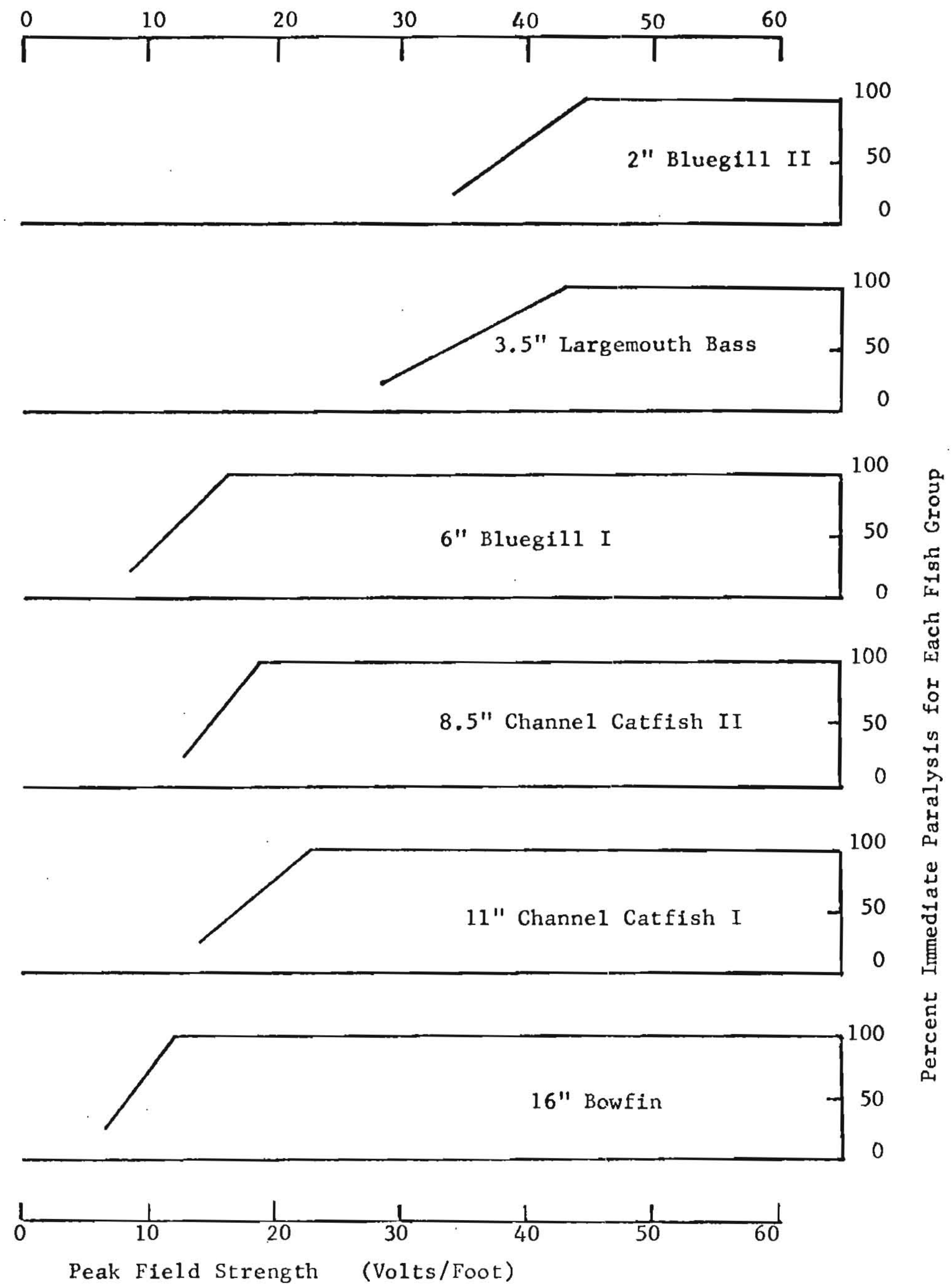


Figure 40. Percentage immediate paralysis versus applied field strength for each of the fish groups tested using a 25 PPS rectangular waveform of 0.2 duty factor.

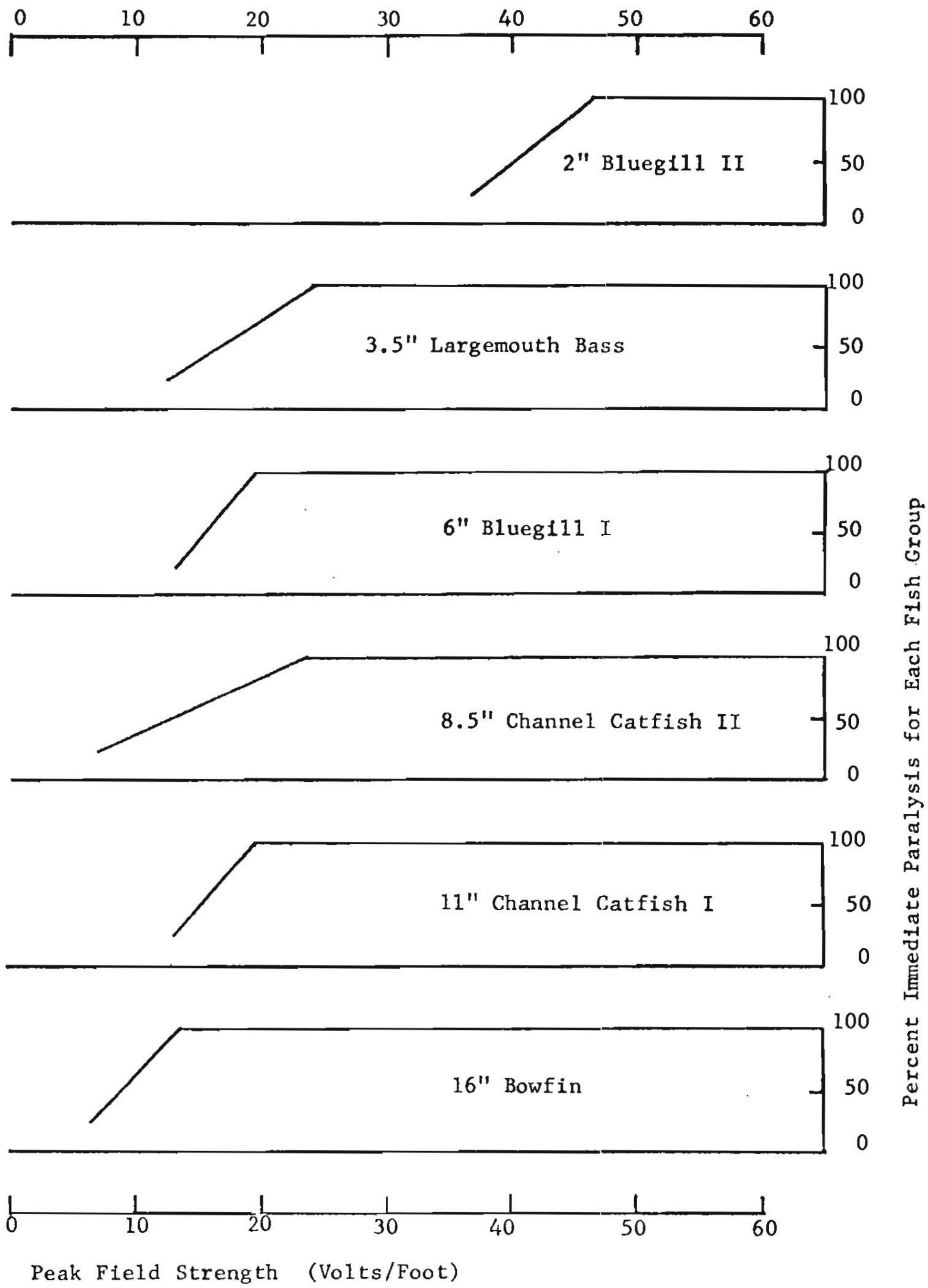


Figure 41. Percentage immediate paralysis versus applied field strength for each of the fish groups tested using a 100 PPS rectangular waveform of 0.6 duty factor.

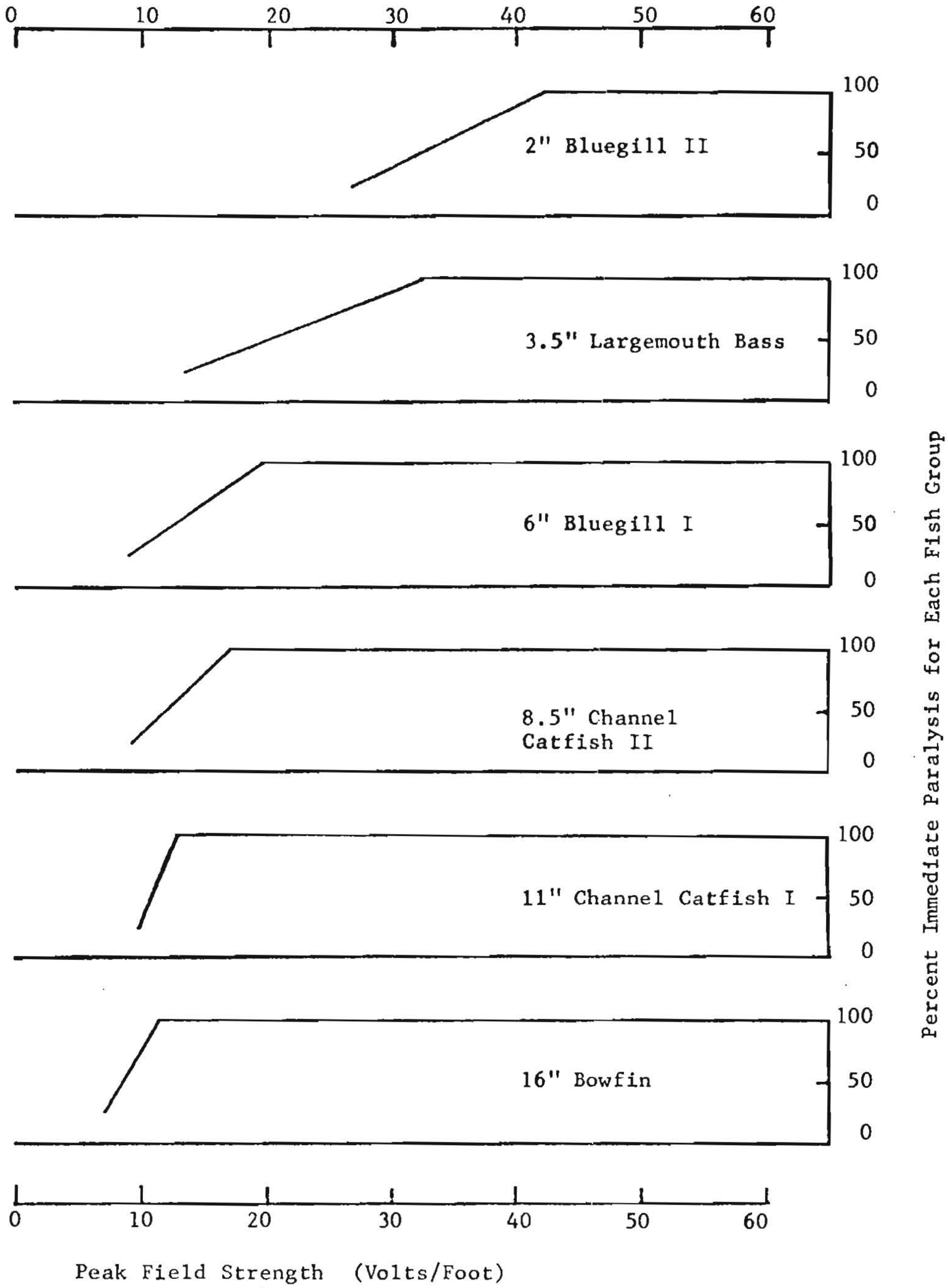


Figure 42. Percentage immediate paralysis versus applied field strength for each of the fish groups tested using a 100 PPS rectangular waveform of 0.2 duty factor.

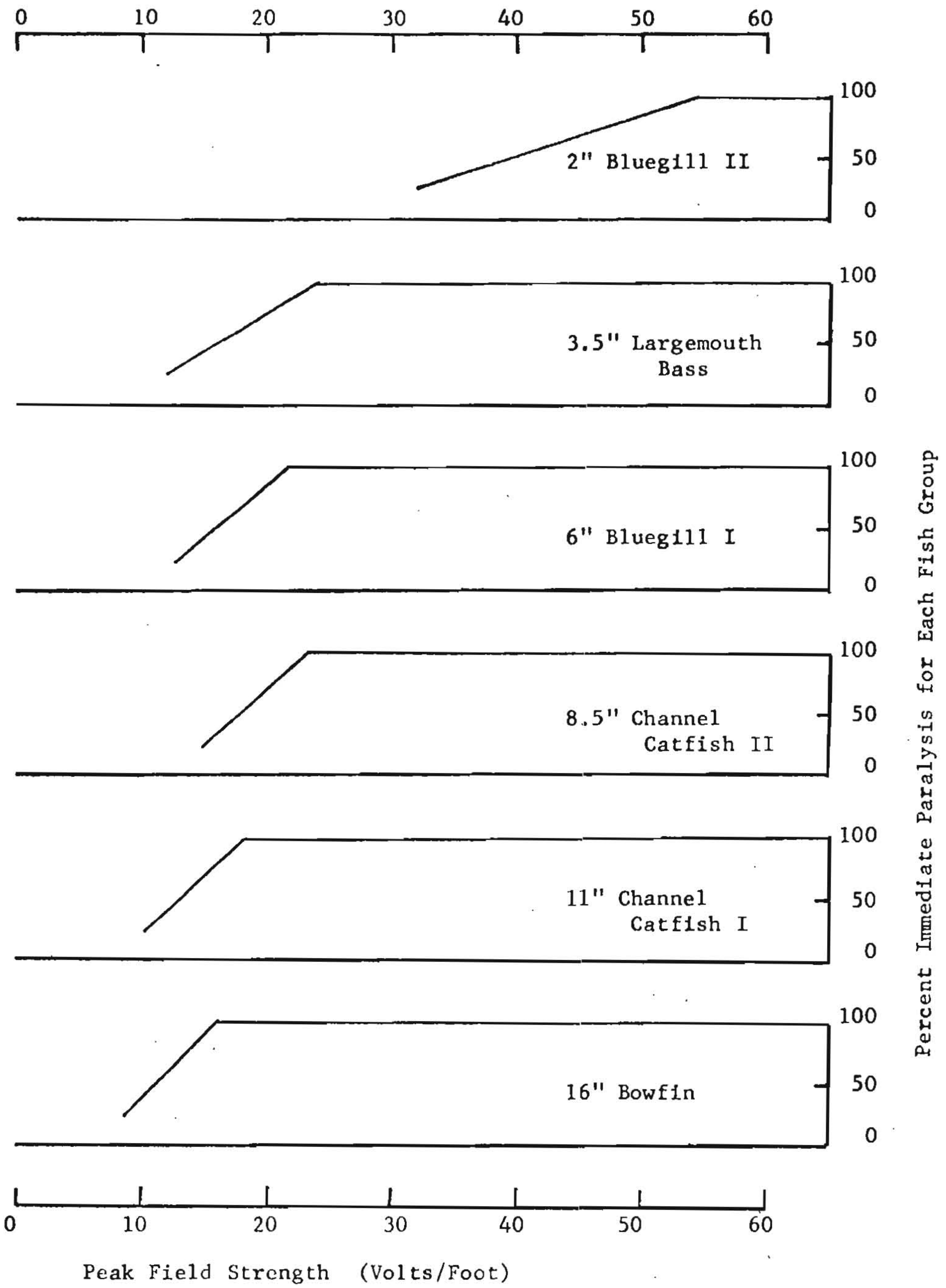


Figure 43. Percentage immediate paralysis versus applied field strength for each of the fish groups tested using a 200 PPS rectangular waveform of 0.6 duty factor.

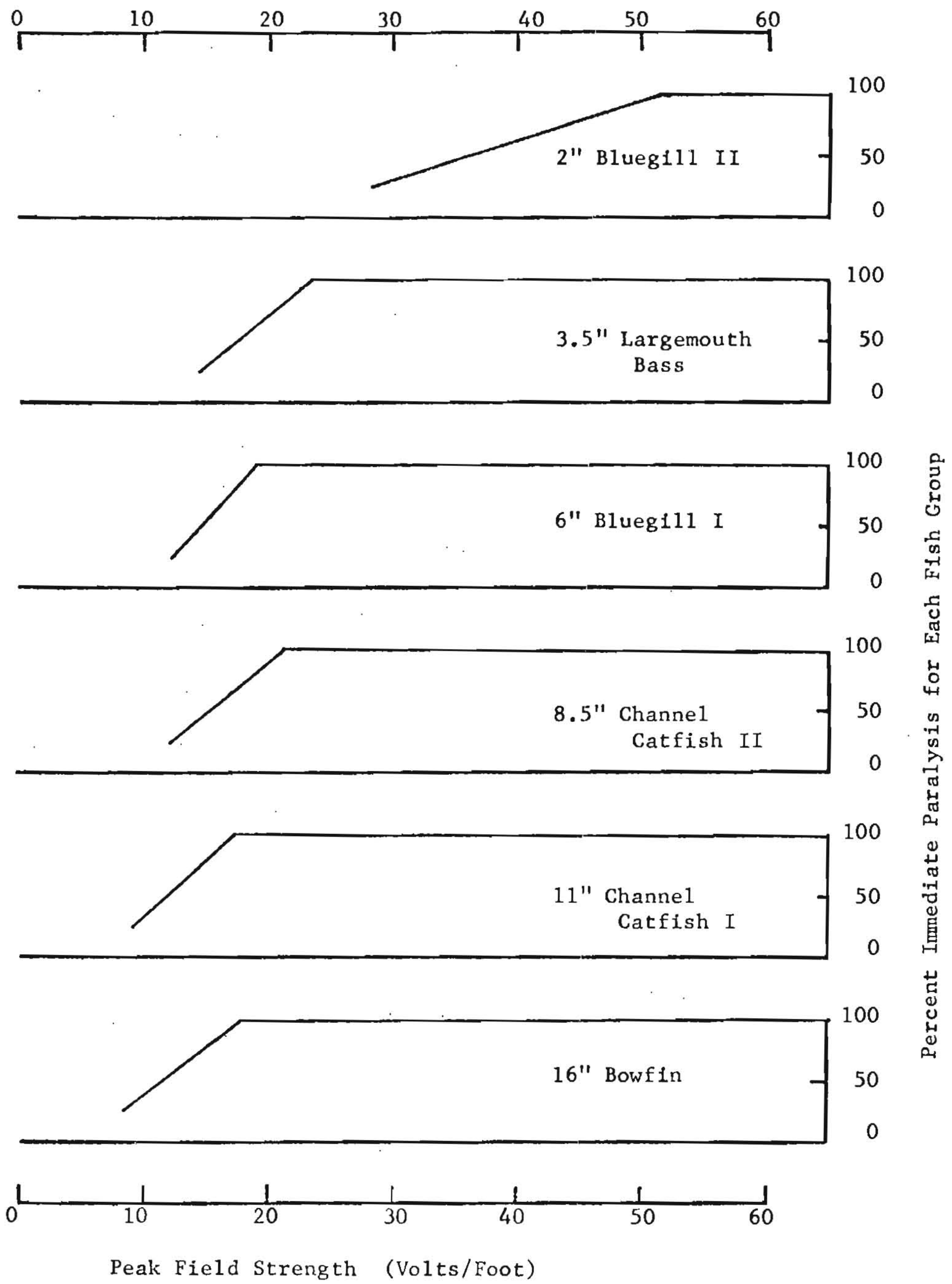


Figure 44. Percentage immediate paralysis versus applied field strength for each of the fish groups tested using a 200 PPS rectangular waveform of 0.2 duty factor.

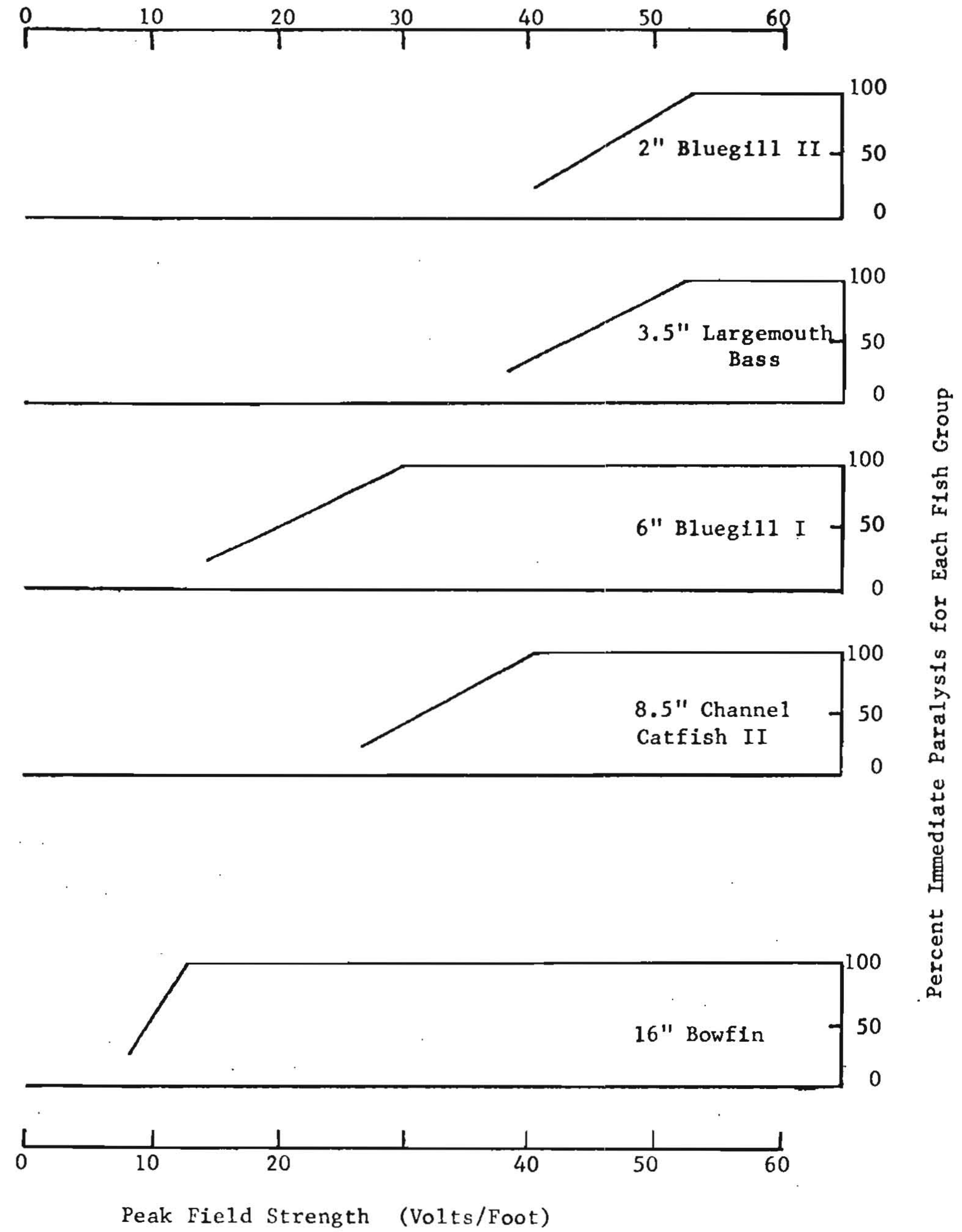


Figure 45. Percentage immediate paralysis versus applied field strength for each of the fish groups tested using a 25 PPS exponential waveform of 3.0 millisecond time constant.

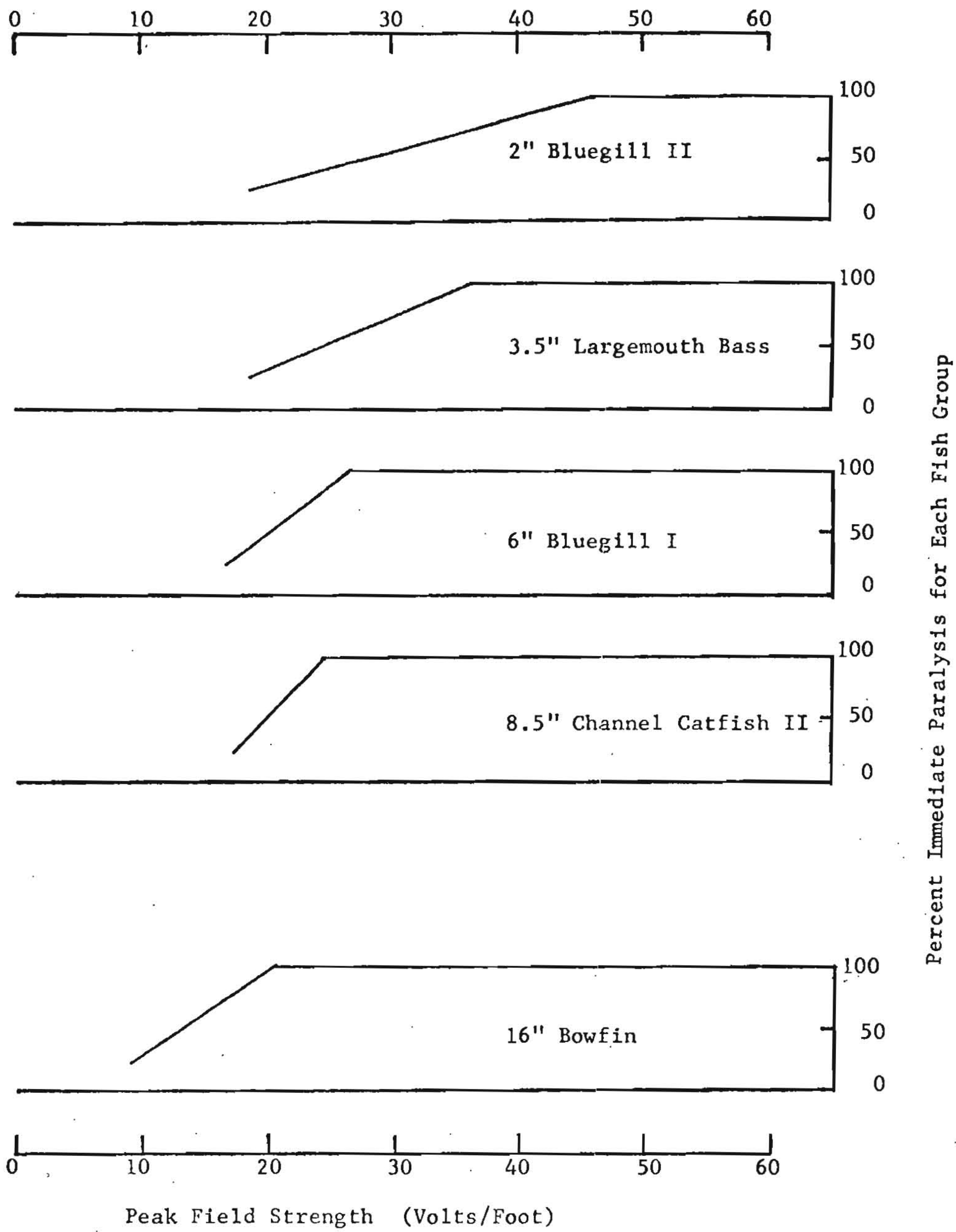


Figure 46. Percentage immediate paralysis versus applied field strength for each of the fish groups tested using a 100 PPS exponential waveform of 0.6 millisecond time constant.

paralyzed by a given field. For example, Figure 35 indicates that a field strength of 35 volts per foot at dc should paralyze 100% of the 8.5-inch and 11-inch catfish and the 16-inch bowfin, almost none of the 2-inch bluegill, 6-inch bluegill, and 3.5-inch bass. A dc field strength of 58 volts per foot or more should paralyze 100% of all six groups of fish. Figure 44 indicates that with 200 rectangular pulses per second having a 0.2 duty factor, a peak field strength of 24 volts/foot will paralyze all the groups of fish except the 2" bluegill. Very few of these small ones will be immobilized. Figure 45 indicates that with exponential pulses having a 3 millisecond time constant and frequency of 25 pulses per second, a peak field strength of 13 volts/foot or more will paralyze 100% of the 16-inch bowfin. With this field strength no fish in the other five groups will be paralyzed, except for a small percentage of the 6" bluegill. Figure 35, when compared with Figures 36 through 46, suggests that the greatest differential in sensitivity between the bluegill of 6" average length and bowfin of 16" average length occurs using a dc waveform. Comparing all the waveforms, it appears that the 25 PPS exponential or the 100 PPS exponential waveform might be the most effective at separating the bowfin from the other species tested. None of the tested waveforms appear to be effective in immobilizing channel catfish but not bowfin. Of these waveforms, it appears that dc is the most effective in separating channel catfish from the bluegill and largemouth bass.

It should be noted that for all of the above examples, larger fish can be separated from smaller fish. For no waveform was this trend reversed to the extent that a group of small fish of one species could be effectively separated from a group of larger fish of another species.

If it is desired to affect all species equally in an attempt to get an accurate sample of the fish population, the results indicate that burst waveform (Figure 36) would be the most effective of those investigated. With the exception of the 2" bluegill, all the 100 percent paralysis points fall within a field strength range of 15 to 19 volts per foot.

It should be emphasized again that these data are only roughly approximate, at best. The numbers of fish tested were too small and the sizes within each group were spread over too wide a range to allow anything more than rough indications to be given, but in spite of the limitations of the data, perhaps some useful conclusions can be drawn.

Power Reductions

The foregoing data have also been used to investigate the possibility of reducing, through waveform selection, the average power required for electrofishing. If substantial reductions in average power can be achieved, smaller and lighter portable shockers could become practical and the effectiveness of boat-mounted shockers could be increased.

The average power expended is proportional to the duty factor of a waveform and to the square of the applied voltage. Thus, reducing the duty factor to ½ its value reduces the average power by ½, but reducing the applied voltage by ½ reduces the average power to ¼ of its original value.

Figures 47 through 52 indicate the relative efficiency of the twelve waveforms in paralyzing the six groups of fish by displaying for each waveform the average power required to paralyze 3 fish out of 4. A scale of watts is given to show the rate at which power was expended in the experimental shocking tank. The actual wattage values are not important because these

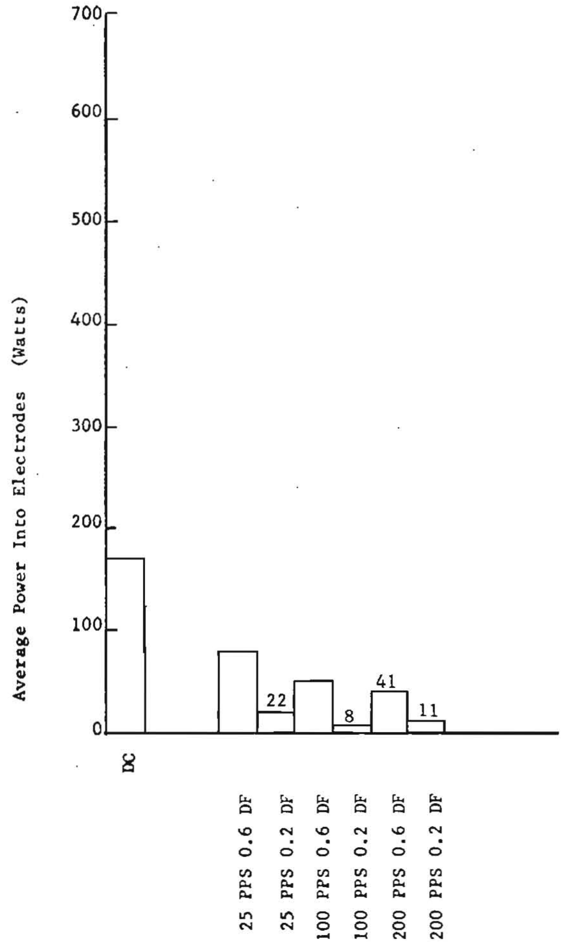


Figure 47.
Power required to produce immediate paralysis in 75% of the Channel Catfish I of average length 11" for various waveforms tested.

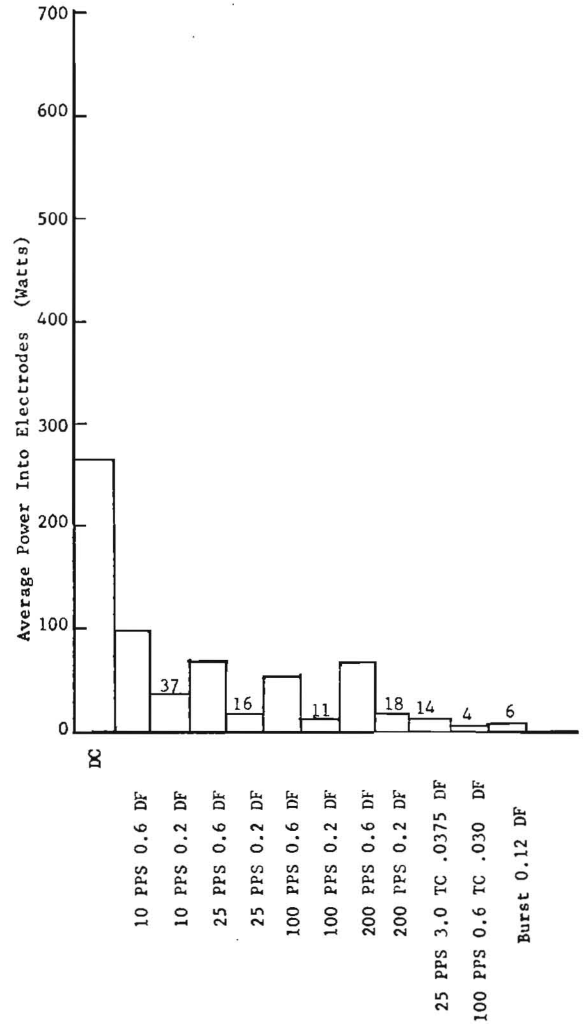


Figure 48.
Power required to produce immediate paralysis in 75% of the Channel Catfish II of average length 8.5" for various waveforms tested.

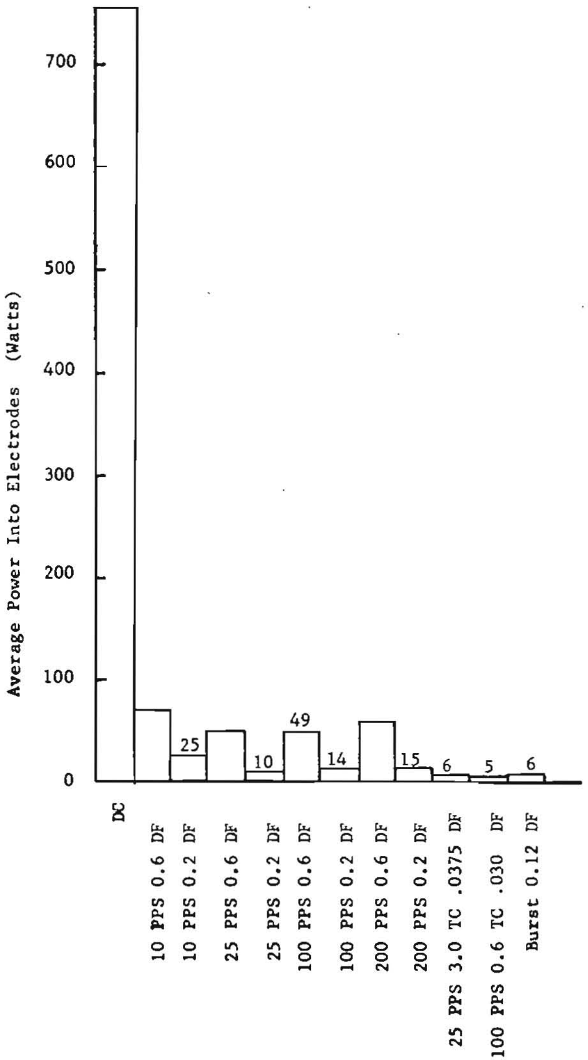


Figure 49.
Power required to produce immediate paralysis in 75% of the Bluegill I of average length 6" for various waveforms tested.

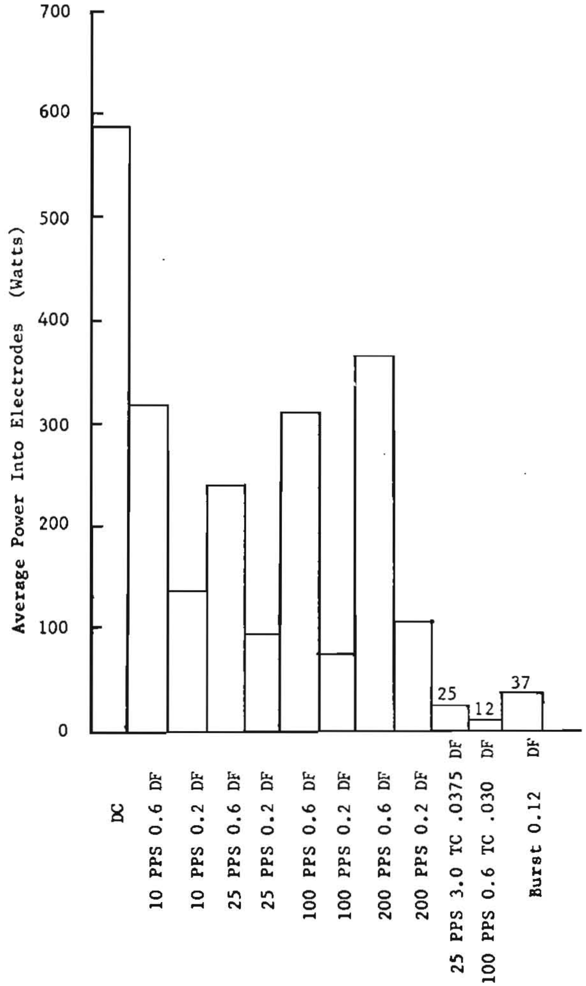


Figure 50.
Power required to produce immediate paralysis in 75% of the Bluegill II of average length 2" for various waveforms tested.

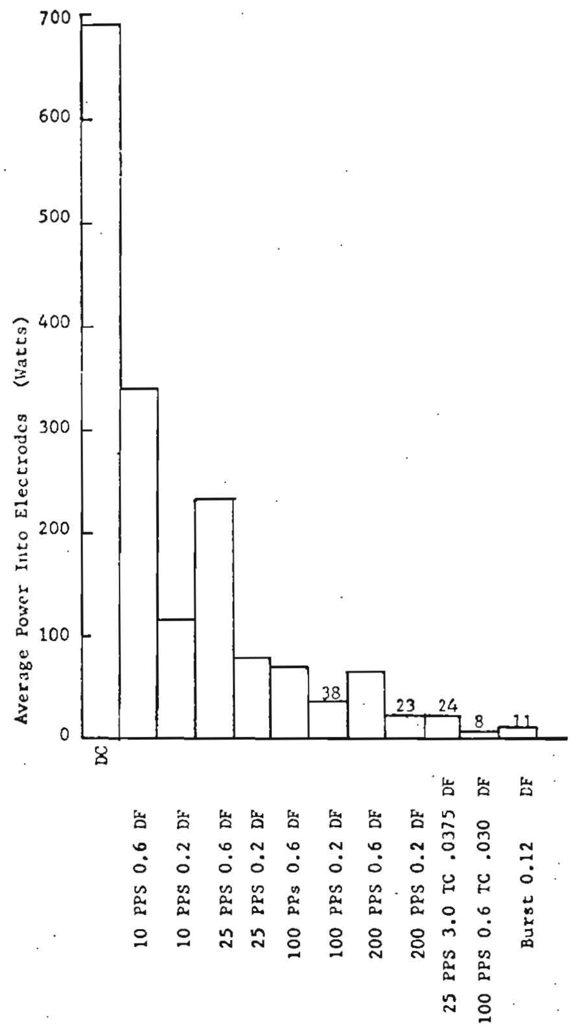


Figure 51.
Power required to produce immediate paralysis in 75% of the Largemouth Bass of average length 3.5" for various waveforms tested.

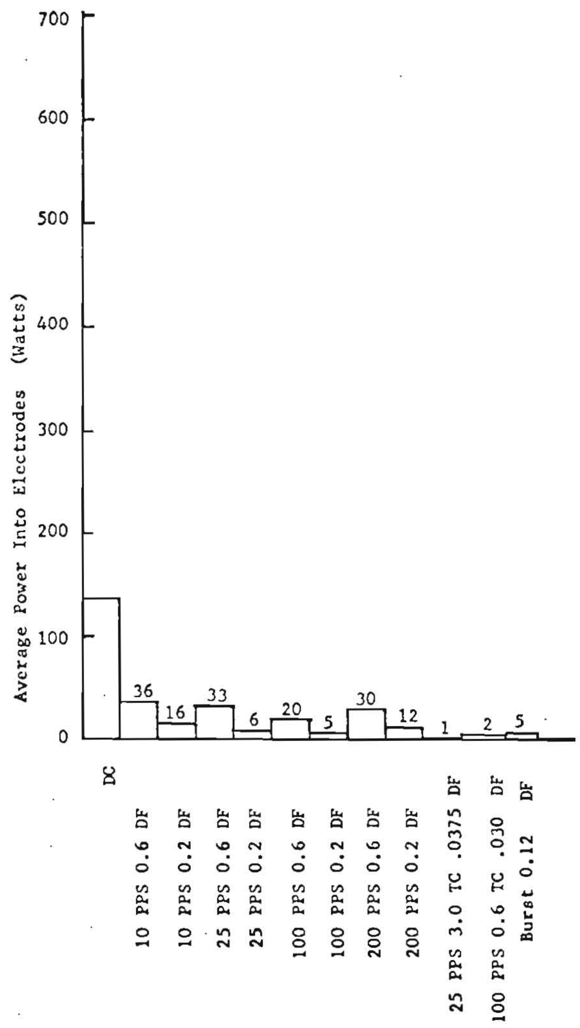


Figure 52.
Power required to produce immediate paralysis in 75% of the Bowfin of average length 16" for various waveforms tested.

depend on the conductivity of the water, the shape and placement of the electrodes, and several other variables. The comparison of the amounts of power required by the different waveforms is the important feature of these figures. Clearly, very large reductions in power are possible in comparison to the power required by steady dc. The most effective of the rectangular waveforms in terms of average power are those with shorter pulse lengths (0.2 duty factors), and the burst waveform requires even less power than these. The waveform requiring the lowest average power is, in most cases, the 100 PPS exponential waveform. These data show that by changing the waveform from dc to a pulsed form, the power required to paralyze 3 fish out of 4 in any of the six groups can be reduced by 92 to 99%. This reduction is substantial indeed and is of great practical significance.

It would be interesting to know how short a pulse (or how small a duty factor) can be utilized without loss of effectiveness. In the case of the 2-inch bluegill, a 100 PPS rectangular pulse train with a duty factor of 0.1 was tested in addition to the twelve usual waveforms. No significant loss of effectiveness in terms of peak voltage was measured. The power required was therefore about half that required by the standard 0.2 duty factor pulse train. The exponential pulse trains of 3 and 0.6 millisecond pulses had equivalent factors of 0.0375 and 0.030 respectively, and the latter appears to require the least power of all. (See Figure 50.) The question then is, how far can the duty factor be reduced? What duty factor requires the least power, and what pulse shape should be used? Clearly, more data are required to determine how small the duty factors of the rectangular and exponential pulse lengths can be made without loss of effectiveness on the fish, and to determine whether, with pulses of an optimum length, the burst technique can be used to reduce further the average power required.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

The motivation for this study of the responses of fish to electric currents was an interest in investigating (1) the possibility of selectively immobilizing a particular species or size of fish by an appropriate choice of electrical waveform and (2) the possibility of reducing the required amount of electrical power through the use of more effective pulse shapes and frequencies.

Earlier work indicated that pulsating dc currents were the most effective for electrofishing through the inducement of temporary immobilization of fish. Accordingly, rectangular and exponential pulse shapes were tested at frequencies up to 200 pulses per second. The basis on which the various waveforms were compared was the value of the peak field strength required to immobilize 75% of a group of similar fish. Twelve different waveforms were tested on six groups of fish representing four species.

With regard to selectivity, the data show clearly that large fish are generally more susceptible to electric shocks than small fish. This difference is probably due to the fact that when an electric current creates a voltage gradient in the water, a large fish intercepts more of the gradient than a small fish and thus is exposed to a larger voltage difference.

Variations in the reactions of different species were difficult to discern from the present limited quantity of data. The test specimens of different species were also of different sizes, and variations in response which might have been attributed to species were obscured by the variations due to differences in size. The present data include too few frequencies and too few sizes of fish to draw any definite conclusions on this point.

However, the fact that large fish are more susceptible to electric shocks than small fish can be used to advantage in a number of ways. By using the proper waveform and peak voltage with a suitable electrode configuration, it should be possible to paralyze and collect fish larger than a certain minimum size. If a particular population survey were interested in only one species of fish, this technique could be used to separate the larger fish from the smaller. On the other hand, the technique could be used to separate fish of different species if the species of interest tended to grow to a larger size than the other species. In some locations, for example, bowfin could be separated from other fish because of their size.

It would be desirable to make laboratory tests of the suggested technique both by using fish of a single species but of varying sizes and by using fish of several different species and sizes. A successful series of laboratory tests should be followed by tests in the field.

Since the present data do not indicate any gross differences in the reactions of the four species tested to the twelve test waveforms, further work is required to determine ways of affecting one species without affecting another. The possibility of shaping a waveform so that it is exceptionally effective on a single species should be investigated. Brain wave data might provide clues as to the waveforms or frequencies which should be investigated. Information concerning the physiological mechanisms of paralysis would also be helpful in this connection, and an investigation of these mechanisms should also be conducted.

The present investigation into the reduction of power requirements by waveform selection was notably successful. Three techniques were demonstrated to be effective in reducing significantly the required average power: (1) reduction of duty factor (2) use of exponentially decaying pulses, and (3) periodic interruption of the pulse trains. Power reductions of 92 to 99% as compared with steady dc were demonstrated, and there is no indication that minimum power levels required to produce immobilization have been reached. These results appear to be potentially significant in several aspects of electrofishing:

(1) A light-weight, battery-powered, solid-state portable shocker seems to be within the realm of feasibility for waters of moderately low conductivity. Such a device would be less fatiguing to the operators, and would require far less maintenance than gasoline powered units. In addition, it would be silent in its operation and therefore not as apt to scare the fish away. Perhaps rechargeable dry cell batteries could be used for convenience and economy.

(2) A significant increase in the effective working area of boat-mounted shockers should be possible. Again, battery-powered units could capitalize on advantages mentioned above. The increase in effective area would be most advantageous if coupled with a field generating technique that would herd fish toward the surface near the boat.

It should be pointed out that in the design of circuitry and selection of output waveforms there may be significant practical considerations other than the efficient use of electrical power. Transformer size and weight considerations could make higher repetition frequencies significantly more attractive than lower frequencies. Component cost considerations might favor exponential waveforms over rectangular.

The results of this investigation of power requirements lead us to suggest two courses of action. On one hand, we now have sufficient knowledge to build a portable, battery-powered shocker which, in our opinion, would have significant advantages over units presently in use. Field tests of such a unit would be valuable in verifying the conclusions of the present study. On the other hand, the three techniques mentioned above for reducing power requirements can be further developed with the collection of additional data. With the present laboratory equipment, it should be possible to determine a practical minimum for power requirements by using shorter pulses, exponentially decaying pulses, and interrupted pulse trains. We feel that both courses of action will be helpful in the effort to improve the efficiency of present electrofishing techniques.

GLOSSARY

Definitions of terms as used in this report.

anode - The positively charged electrode.

burst waveform - A train of pulses which is interrupted periodically, a "dual frequency pulse" in Burnet's [3] terminology; specifically in this investigation a pulsed waveform produced by periodically interrupting a rectangular pulse train having a frequency of 200 pulses per second and 0.2 duty factor, so as to eliminate 3 pulses from each group of 8 consecutive pulses (See Figure 7).

cathode - The negatively charged electrode.

conductivity - An intrinsic quality of the water which measures its capability to conduct an electric current. It may be measured in mhos per centimeter. The conductivity, electrode configuration, and electrode placement will determine the inter-electrode resistance.

dc - Direct current; in the present application, a non-fluctuating current passing through the electrodes.

duty factor - Average power divided by peak power. For a rectangular pulse train, this factor expresses the fraction of time the electric current is flowing.

electrodes - Metallic conductors which carry the current into and out of the water and determine the electric field configuration in water.

field strength - The intensity of the electric field (in the water). It may be measured in volts per foot. In a uniform field it is equal to the voltage between the electrodes divided by the distance between the electrodes.

frequency - The number of recurrences, cycles, or pulses per second in a periodic waveform. It is measured in pulses per second (PPS) or Hertz (Hz).

head-to-tail potential - The voltage a fish experiences from its head to its tail. Head-to-tail potential is a function of the field strength and of the length and orientation of the fish. If the fish does not distort the field configuration and is aligned along the direction of current flow, it is the product of the electric field strength (in volts per foot) and the length of the fish (in feet).

inter-electrode resistance - The voltage between the electrodes divided by the current flowing between the electrodes, i.e., the electrical resistance between the electrodes.

millisecond - One thousandth of a second (0.001 second).

narcosis - State of immobility resulting from muscular slackening.

peak field strength - The maximum field strength occurring during a repeating waveform.

peak voltage - The maximum voltage that occurs between the electrode during a repeating waveform.

period - The time of one complete repetition of a repeating waveform; the reciprocal of frequency.

potential - Voltage.

power - Energy per unit time; the square of the voltage between two electrodes divided by the inter-electrode resistance.

pulse - A single application and removal of voltage to the electrodes.

pulse train - A sequence of pulses.

pulse width - The duration of a rectangular pulse.

rectangular waveform - A waveform in which the voltage switches between two different constant levels, such as the peak voltage and zero volts.

shock generator - Power source which supplies current to the electrodes.

tetanic condition - A state of immobility resulting from muscular rigidity (tetanus).

time constant - A measure of the rate of decay of an exponentially decaying voltage; the time required for a voltage to decay to 37% of its initial value.

waveform - A description of a voltage as a function of time, often expressed graphically as in Figures 2 and 7.

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