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EXPLORATORY EXPERIMENTS IN GUIDING SALMON FINGERLINGS BY A NARROW D.C. ELECTRIC FIELD

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EXPLANATORY NOTE

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United States Department of the Interior, Douglas McKay, Secretary
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EXPLORATORY EXPERIMENTS IN GUIDING SALMON FINGERLINGS BY A NARROW D. C. ELECTRIC FIELD

by

Parker S. Trefethen
Fishery Research Biologist

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ABSTRACT

The effectiveness of one type of narrow direct-current electrical field in diverting salmon fingerlings in flowing water was explored experimentally in relation to (1) the angle of the electrical field relative to the direction of water flow, (2) the width of the electrical field (distance between rows of electrodes), (3) the spacing between electrodes, and (4) the diameter of the electrodes. The electrical conditions were held constant at a voltage gradient of 1 volt/cm., a pulse frequency of 8 pulses/sec., and a pulse duration of 40 milliseconds with a square wave form.

It was determined that under the conditions of these experiments the maximum effectiveness occurred at a 40° angle of electrical field and a 2-foot width of electrical field with 1/2-inch electrodes spaced 12 inches apart. With few exceptions, the 40° angle of field was not significantly more effective than the 60° angle of field, and the 1/2-inch diameter electrode was not significantly more effective than the 2-inch diameter electrodes. The 2-foot width of field appeared to be more effective than the 3-foot width of field. The results of variation in electrode spacing were greatest at a 40° angle of electrical field.

CONTENTS

INTRODUCTION

The U. S. Fish and Wildlife Service is engaged in research to develop a method of electrically guiding or directing downstream-migrating salmon fingerlings into by-passes away from areas of high mortality. Many fingerlings are injured or killed each year in spillways and turbines of large dams or are swept into irrigation diversions. The mechanical screening used at small installations is generally considered impractical where huge volumes of water are involved.

This research program includes experiments which range from large-scale field trials to the seeking of basic information on the electrical characteristics and energy levels effective in controlling the movements of salmon fingerlings (Collins, Volz, and Lander, unpublished manuscript) and the relation of these to the electrical characteristics and energy levels injurious to the fingerlings (Collins, Volz, and Trefethen, 1954).

The present research, an intermediate step between basic laboratory experiments and full-scale field trials, was designed to test the effectiveness of one type of a narrow direct current field in diverting salmon fingerlings in flowing water in relation to the following factors:

(1) The angle of the electrical field relative to the direction of water flow.

(2) The width of the electrical field. (Distance between row of electrodes).

(3) The spacing between electrodes.

(4) The diameter of electrodes.

METHODS AND MATERIALS

The experiments were conducted in a large concrete tank 24 feet wide and 30 feet long, with a maximum depth of 16 inches. A coat of insulating paint was applied to the inside of the tank to prevent distortion of the electrical field. The water level was maintained at 9 inches and circulation of the water during the experiments was maintained by a recirculating pump. Plywood vanes and a plywood island were used as aids in keeping a relatively uniform flow of water through the experimental area which was approximately 18 feet long and 10 feet wide (fig. 1).

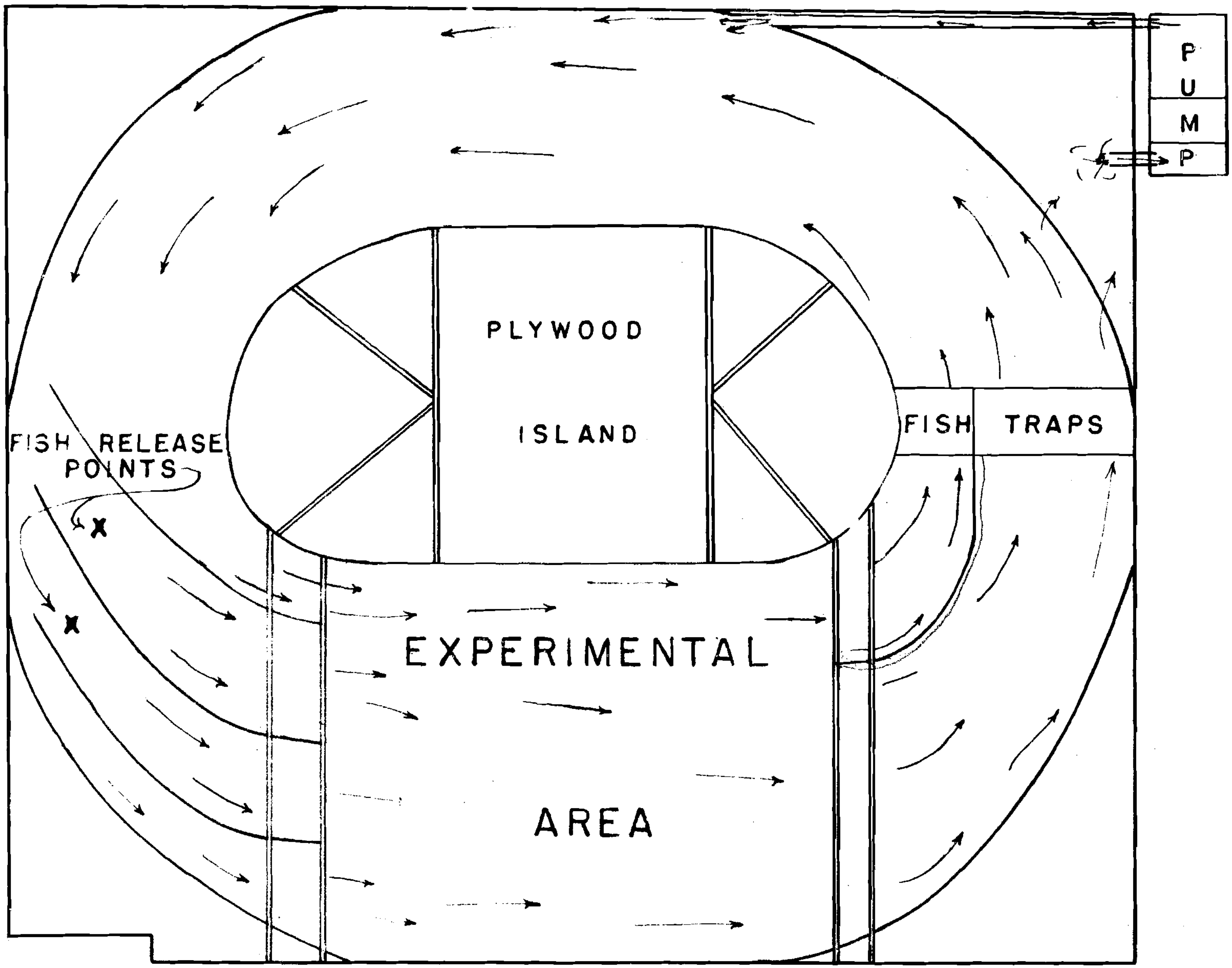

Fig. 1. A plan view of concrete tank in which experiments were conducted.

The lower or downstream end of the experimental area was divided by a plywood vane into two channels with entrances 3 feet and 7 feet wide respectively. Besides directing the flow of water around the island, the plywood vanes served to separate the fish that were diverted by the electrical field into the narrow channel from those that passed through the electrical field into the wide channel. Baffle-type traps constructed from 1/4-inch-mesh galvanized hardware cloth collected the fish in the two channels.

The electrical barrier was created by two parallel rows of electrodes suspended from wires stretched across the experimental area. The parallel wires were adjustable at angles at 40°, 60°, and 90° in relation to the long axis of the experimental area; the wires could be spaced 2 or 3 feet apart (fig. 2). The distance between these wires is designated as the width of the electrical field. Electrodes of hollow aluminum tubes were fastened to each wire by slim-nosed alligator clips at 6, 12, 24, and 36-inch spacings: they were suspended in the water to within 3/4 inch of the bottom of the tank. For a comparison, electrodes of 1/2- and 2-inch outside diameters were used. A pulsating direct current with a square wave form was supplied to the two rows of electrodes with the positive row upstream. To eliminate the possibility of a visual leading effect, two parallel rows of control electrodes suspended from nonconductive material were placed opposite the rows of electrodes which were electrified; both sets of electrodes were in the water at the same time. Figure 2 illustrates a typical arrangement of both test and control electrodes used in the experiments.

Light was supplied by four 500-watt lamps spaced uniformly over the tank. A variable auto-transformer controlled the light intensity between 3.4 foot-candles and less than 1 foot-candle. During the tests the light intensity was reduced in order to stimulate a downstream movement of the salmon fingerlings. Under maximum light intensity the fish tended to school in the experimental area and any attempt to force them downstream resulted in startled swimming movements. All changes in intensity were made very gradually to avoid startling the fish.

A pulsating square-wave direct current was supplied to the barrier with the following characteristics: pulse frequency 8 pulses per second, pulse duration 40 milliseconds, and voltage gradient 1 volt per centimeter. These electrical characteristics and energy levels were found to be effective in the preliminary experiments of Collins, Volz, and Lander (unpublished manuscript).

The total voltage was measured with a standard RCA WO-56-A oscilloscope; the voltage gradient was calculated from the total voltage and the distance between the parallel rows of electrodes. The voltage gradient represents an average value since the electrical field resulting from the tubular electrodes was not uniform. The actual voltage gradients were measured with a probe (fig. 3). The lines of equal potential resulting from one arrangement of electrodes are shown in figure 4.

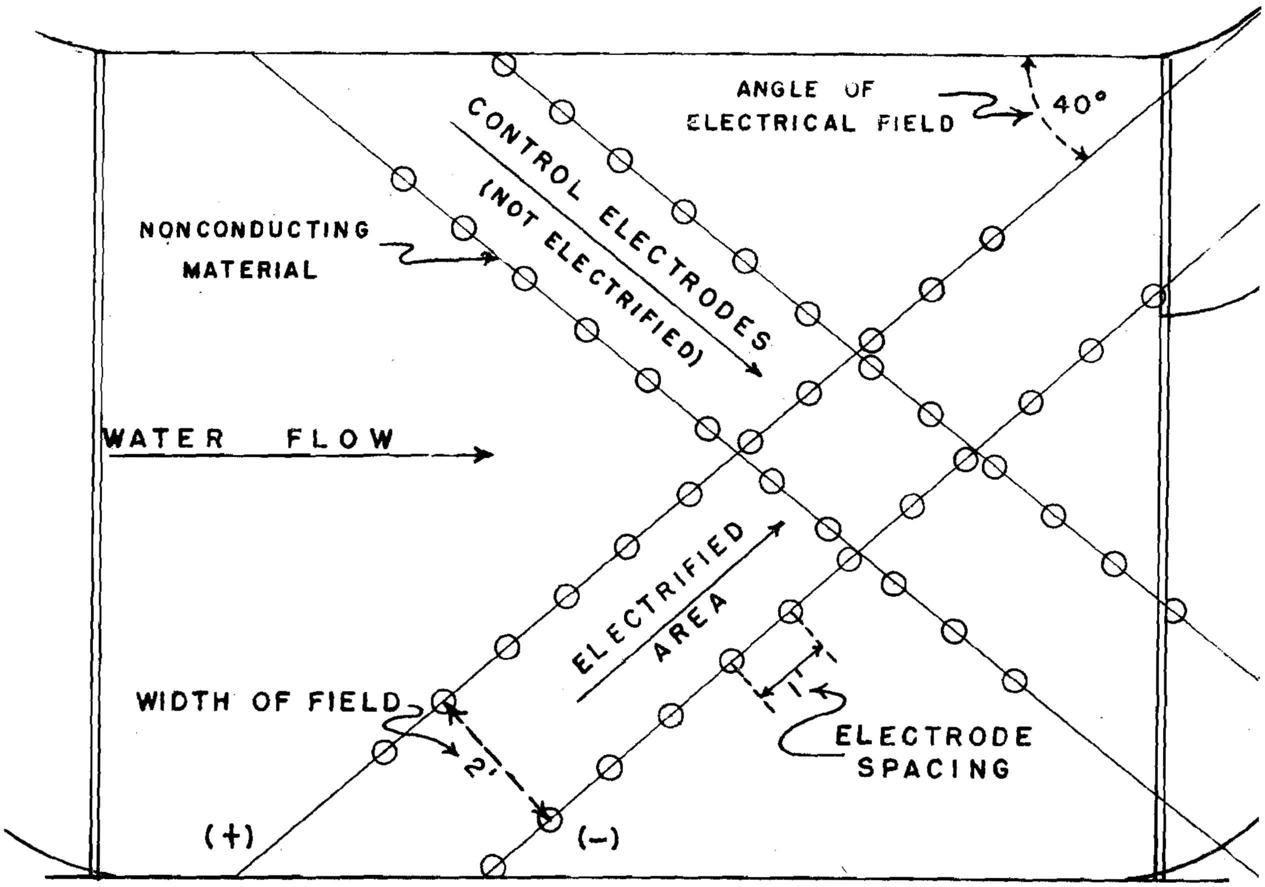

Fig. 2. A plan view of the experimental area with a typical arrangement of electrodes.

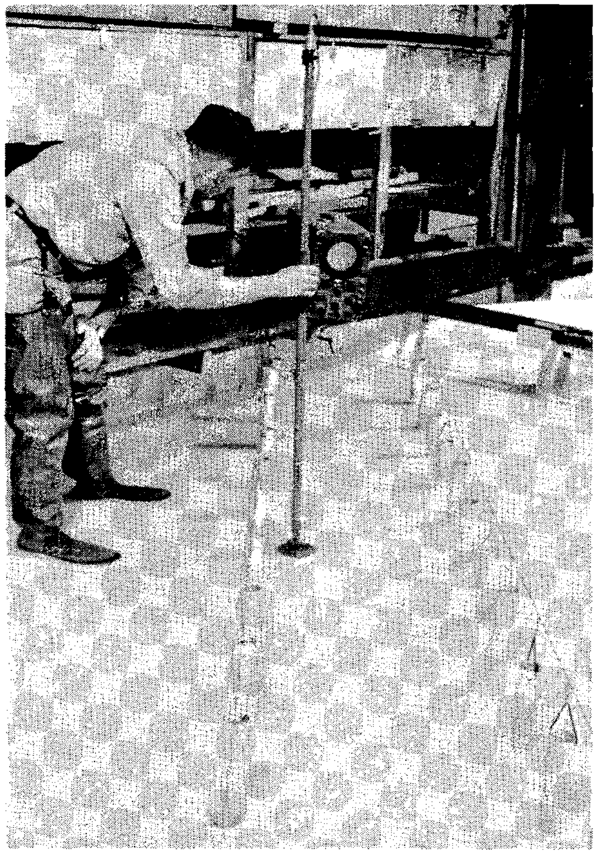

Figure 3. Measuring the electrical field with special probe. Electrode arrangement shown includes the following: (1) angle of electrical field 40°, (2) width of electrical field 2 feet, (3) spacing between electrodes 12 inches, (4) diameter of electrodes 2 inches.

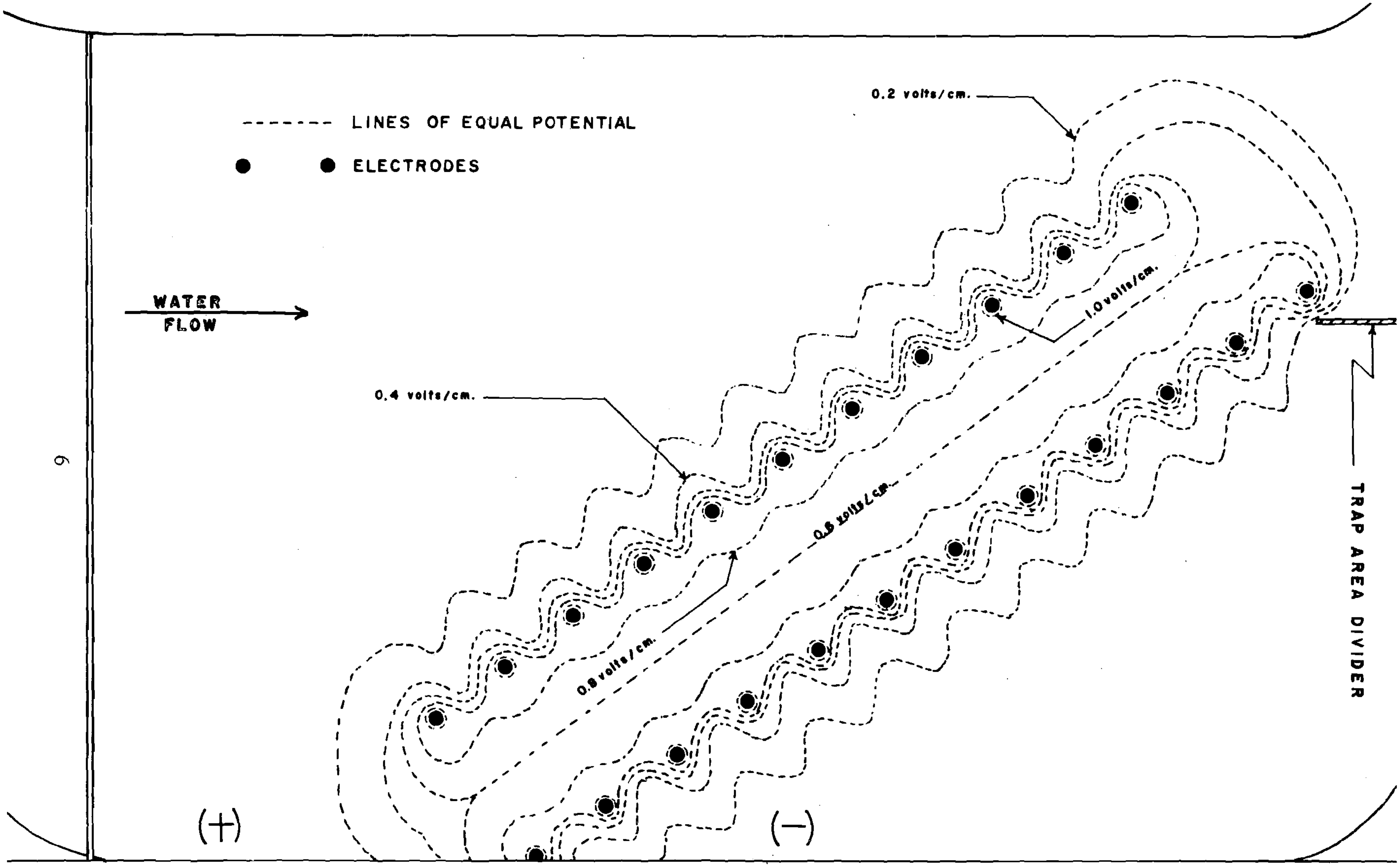

Fig. 4. Diagram of equal potential lines around 2-inch electrodes spaced 12 inches apart at a 40° angle of electrical field and a 2-foot width of electrical field; there are 60 volts between lines of electrodes.

Pulse frequency and pulse duration were both measured on a special oscilloscope designed and constructed for laboratory experiments in fish guiding (Volz, unpublished manuscript).

Water resistance was maintained between 7,250 ohms/cm.^{3} and 10,000 ohms/cm.^{3}; it was determined by an industrial Instruments Conductivity Bridge Model RC-1B. Water temperature varied between 8.0° C. and 16.0° C. and was determined with a standard mercury thermometer. Water resistance and the temperature were recorded before each series of tests.

Silver salmon (Oncorhynchus kisutch) ranging in size from 5.5 cm. to 12.0 cm. total length, measured from the tip of the snout to the end of the tail, the only species used in these tests, were obtained weekly at the Washington State Fish Hatchery at Issaquah, Washington, and transported to the laboratory in Seattle where they were placed in round metal holding tanks. Immediately prior to use they were removed in small lots of from 150 to 200 fish and placed in a smaller trough near the experimental area from which they were taken in groups of 60 fish for each test.

Four groups of fish were used each time for each test condition. Two of the groups of fingerlings (2d and 3d) were released while the electrodes were supplied with electrical energy and two groups (1st and 4th) were released when the electrical energy was not supplied; the 1st and 4th groups of fish were designated as control groups to ensure that an increase in numbers found in the narrow channel was the result of the electrical field and not due to the changes in hydraulic patterns created by the electrodes or leading as the result of a visible barrier.

The fingerlings that were exposed to the electrical current and recovered from the traps were returned to a second round metal holding tank until all fish on hand had been exposed once; this procedure was followed to maintain the same condition for all fish in any series of tests. Since preliminary tests had indicated that conditioning might influence the behavior of fish exposed three or more times to electrical conditions, the fingerlings were exposed only twice; the same handling procedure was followed in every experiment. The control group of fingerlings, that had not been exposed to electrical energy, were returned to the original tank from which they were taken until they had been exposed to electrical conditions, after which they were handled as described above.

Prior to release of the fish, the light intensity was subdued to less than 1 foot-candle and the electrodes were energized. The salmon fingerlings were then released in groups of 60 individuals upstream from the experimental area (fig. 1) equally divided into the two middle channels. (On the one exception to this procedure, 200 fish were released to investigate the effect with large numbers). Once the fish were released the light intensity was reduced to a minimum and the tank remained in almost total darkness for 5 minutes. At the end of that time, the light intensity was very slowly increased to a maximum.

The entrances to the two channels on the downstream end were blocked off with plastic screens and the electrodes de-energized before a total count of the fish in the traps was made. Before subsequent tests the experimental area was entirely cleared of fish by forcing them into the channels at the upstream end.

The results were calculated on a percentage basis from the total number of fingerlings recovered in both traps and the total number recovered in the narrow channel. The index of effectiveness is defined as the difference of the percentage of control fish collected in the narrow channel and the percentage of fish collected in the narrow channel following an electrical test during which the electrodes were energized.

Before a useful comparison between a pair of electrical tests could be made, three preliminary conditions had to be satisfied: (1) The respective controls had to be uniform, (2) The mean percentages of fingerlings recovered in the narrow channel had to be the same and (3) The electrical tests being compared had to be uniform. While nonuniformity could result from a response distribution with a large variance, the foregoing restrictions guarantee a uniform experimental technique. All tests of uniformity and of equal mean percentages were chi-square tests of significance at the 5-percent level. The results of these tests are shown in tables 1 to 12.

EXPERIMENTS

In exploring the effectiveness of a narrow d.c. field under laboratory conditions, the electrical characteristics and energy levels were held constant while the following factors were varied: (1) angle of electrical field in relation to the flowing water; (2) width of electrical field (distance between rows of electrodes); (3) spacing between electrodes and (4) diameter of electrodes. These experiments were exploratory in nature and since the results varied considerably, it was difficult to interpret the data conclusively. However, the results have been summarized in tables 13 to 18 and graphically presented in figures 5 to 15.

A maximum effectiveness occurred with a 2-foot width of electrical field (fig. 5). This maximum effectiveness occurred at a 40° angle of electrical field with 1/2-inch electrodes spaced 12-inches apart. At the 40° angle and with 1/2-inch electrodes the 2-foot width of field was significantly more effective than the 3-foot width of field. The difference in effectiveness between 2- and 3-foot fields was greatest at the closer electrode spacings. As the electrode spacing increased from 12 to 36 inches there was a decrease in the difference of the effectiveness of the two widths of field; the effectiveness of the 2-foot width of field also decreased.

At a 60° angle of electrical field with 1/2-inch electrodes the 2-foot width of field appeared to be more effective than the 3-foot width (fig. 6). The difference in effectiveness was greatest at a 6- and 36-inch electrode spacing.

Table 1. Results of Tests for Uniformity of Control Tests when using a 2-foot Width of Electrical Field with $\frac{1}{2}$-inch Electrodes

Electrode Spacing (inches)	Angle of Electrical Field (degrees)	No. Collected in Traps	No. Collected in Narrow Channel	$p > .05$ (uniform)	$p < .05$ (not uniform)
6	40	48	15		
		49	16	X	
	60	69	24		X
		52	9		
	90	49	12		
		65	14	X	
12	40	30	6		
		66	9	X	
	60	62	15		
		74	16	X	
	90	60	10		
		52	10	X	
24	40	62	15		
		56	19	X	
	60	55	14		
		56	10	X	
	90	76	16		
		56	9	X	
36	40	66	16		
		24	8	X	
	60	61	10		
		71	12	X	
	90	48	13		
		55	7	X	

Table 2. Results of Tests for Uniformity of Control Tests when using a 2-foot Width of Electrical Field with 2-inch Electrodes

Electrode Spacing (inches)	Angle of Electrical Field (degrees)	No. Collected in Traps	No. Collected in Narrow Channel	$p > .05$ (uniform)	$p < .05$ (not uniform)
6	40	54	21		
		64	18	x	
	60	60	15		
		50	10	x	
	90	58	8		
		62	10	x	
12	40	66	17		
		37	9	x	
	60	55	14		
		60	16	x	
	90	58	17		
		64	7		x
24	40	50	18		
		46	7		x
	60	57	14		
		60	9	x	
	90	64	15		
		57	13	x	
36	40	51	9		
		57	10	x	
	60	85	16		
		53	14	x	
	90	58	9		
		60	10	x	

Table 3. Results of Tests for Uniformity of Control Tests when using a 3-foot Width of Electrical Field with ½-inch Electrodes

Electrode Spacing (inches)	Angle of Electrical Field (degrees)	No. Collected in Traps	No. Collected in Narrow Channel	p > .05 (Uniform)	p < .05 (not Uniform)
6	40	49	14		
		69	15	x	
	60	48	15		
		56	9	x	
	90	73	19		
		71	10	x	
12	40	79	26		
		58	12	x	
	60	43	8		
		78	27	x	
	90	57	20		
		70	15	x	
24	40	64	13		
		60	11	x	
	60	79	19		
		63	16	x	
	90	53	13		
		62	12	x	
36	40	63	24		
		63	13		x
	60	34	12		
		47	9	x	
	90	73	16		
		63	13	x	

Table 4. Results of Tests for Uniformity of Control Tests when using a 3-foot Width of Electrical Field with 2-inch Electrodes

Electrode Spacing (inches)	Angle of Electrical Field (degrees)	No. Collected in Traps	No. Collected in Narrow Channel	p > .05 (uniform)	p < .05 (not uniform)
6	40	54	21		
		64	18	x	
	60	60	15		
		50	10	x	
	90	48	13		
		53	13	x	
12	40	57	12		
		60	8	x	
	60	49	13		
		81	16	x	
	90	51	10		
		60	12	x	
24	40	69	12		
		58	17	x	
	60	58	17		
		68	11	x	
	90	77	19		
		55	8	x	
36	40	47	10		
		59	14	x	
	60	33	12		
		52	11	x	
	90	60	6		
		49	16		x

Table 5. Results of Tests for Uniformity of Electrical Tests when using a 2-foot Width of Electrical Field with $\frac{1}{2}$-inch Electrodes

Electrode Spacing (inches)	Angle of Electrical Field (degrees)	No. Collected in Traps	No. Collected in Narrow Channel	$p > .05$ (uniform)	$p < .05$ (not uniform)
6	40	49 53	34 40	x	
	60	No test for uniformity, controls not uniform.			
	90	55 28	27 20	x	
12	40	38 62	26 42	x	
	60	64 70	36 38	x	
	90	59 49	29 26	x	
24	40	65 66	40 36	x	
	60	55 55	27 33	x	
	90	50 55	29 30	x	
36	40	61 65	29 29	x	
	60	54 64	33 31	x	
	90	58 66	24 35	x	

Table 6. Results of Tests for Uniformity of Electrical Tests when using a 2-foot Width of Electrical Field with 2-inch Electrodes

Electrode Spacing (inches)	Angle of Electrical Field (degrees)	No. Collected in Traps	No. Collected in Narrow Channel	p > .05 (uniform)	p < .05 (not uniform)
6	40	75	34		
		65	31	x	
	60	62	26		
		62	28	x	
	90	46	18		
		60	25	x	
12	40	58	37		
		57	39	x	
	60	62	41		
		68	46	x	
	90	No test for uniformity, controls not uniform.			
24	40	No test for uniformity, controls not uniform.			
	60	58	37		
		59	30	x	
	90	57	25		
		63	25	x	
36	40	53	29		
		67	26	x	
	60	59	22		
		52	25	x	
	90	51	22		
		58	20	x	

Table 7. Results of Tests for Uniformity of Electrical Tests when using a 3-foot Width of Electrical Field with $\frac{1}{2}$-inch Electrodes

Electrode Spacing (inches)	Angle of Electrical Field (degrees)	No. Collected in Traps	No. Collected in Narrow Channel	p > .05 (uniform)	p < .05 (not uniform)
6	40	62	21		
		71	31	x	
	60	42	19		
		53	28	x	
	90	58	17		
		42	15	x	
12	40	57	24		
		57	23	x	
	60	59	36		
		43	23	x	
	90	55	18		
		49	15	x	
24	40	59	27		
		59	22	x	
	60	43	29		
		50	27	x	
	90	72	19		
		68	16	x	
36	40	No test for uniformity, controls not uniform			
	60	53	21		
		64	27	x	
	90	57	21		
		52	22	x	

Table 8. Results of Tests for Uniformity of Electrical Tests when using a 3-foot Width of Electrical Field with 2-inch Electrodes

Electrode Spacing (inches)	Angle of Electrical Field (degrees)	No. Collected in Traps	No. Collected in Narrow Channel	$p > .05$ (uniform)	$p < .05$ (not uniform)
6	40	53 72	26 38	x	
	60	68 62	28 32	x	
	90	60 54	19 23	x	
12	40	53 56	29 34	x	
	60	45 57	25 35	x	
	90	60 59	20 19	x	
24	40	39 69	18 31	x	
	60	48 58	21 31	x	
	90	61 63	19 11	x	
36	40	55 62	16 28	x	
	60	52 56	28 25	x	
	90	No test for uniformity, controls not uniform.			

Table 9. Results of Significance Tests Between Angles of the Electrical Field in Relation to Width of Electrical Field, Electrode Diameter, and Electrode Spacing

Electrode spacing (inches)	Angle of Electrical Field (degrees)	Width of electrical field							
		2 feet				3 feet			
		Electrode diameter				Electrode diameter			
		½-inch		2-inch		½-inch		2-inch	
		significant	not significant	significant	not significant	significant	not significant	significant	not significant
6	40-60	1/			x		x		x
	40-90	x		x			x	x	
	60-90	1/			x	x			x
12	40-60	x			x	x			x
	40-90	x		1/			x	x	
	60-90		x	1/		x		x	
24	40-60		x	1/		x			x
	40-90		x	1/		x			x
	60-90		x	x		x		x	
36	40-60		x		x	1/		1/	
	40-90		x		x	1/		1/	
	60-90		x		x	1/		1/	

1/ Control tests not uniform. No test for significance.

Table 10. Results of Significance Tests Between Widths of the Electrical Field in Relation to the Angle of the Electrical Field, Electrode Diameter, and Electrode Spacing

Electrode spacing (inches)	Width of electrical field (feet)	Angle of electrical field											
		40°				60°				90°			
		Electrode diameter				Electrode diameter				Electrode diameter			
		1/2-inch		2-inch		1/2-inch		2-inch		1/2-inch		2-inch	
		significant	not significant	significant	not significant	significant	not significant	significant	not significant	significant	not significant	significant	not sig.
6	2-3	x			x	1/			x		x	x	
12	2-3	x			x		x		x	x		1/	
24	2-3		x	1/			x		x	x		x	
36	2-3	1/			x	x			x		x	1/	

1/ Control tests not uniform. No test for significance.

Table 11. **Results of Significance Tests Between Electrode Diameters in Relation to the Width of the Electrical Field, Angle of the Electrical Field, and Electrode Spacing**

Electrode spacing (inches)	Electrode diameter (inches)	Width of electrical field											
		2 feet						3 feet					
		Angle of electrical field						Angle of electrical field					
		40°		60°		90°		40°		60°		90°	
		significant	not significant	significant	not significant	significant	not significant	significant	not significant	significant	not significant	significant	not significant
6	½ - 2	x		1/			x		x		x		x
12	½ - 2		x		x	1/		x			x		x
24	½ - 2	1/			x	x			x		x		x
36	½ - 2		x		x		x		x		x	1/	

1/ Control tests not uniform. No test for significance.

Table 12. Results of Significance Tests Between Electrode Spacings in Relation to Width of the Electrical Field, Electrode Diameter, and Angle of the Electrical Field

Angle of electrical field (degrees)	Electrode spacing (inches)	Width of electrical field: 2 feet — Electrode diameter ½-inch: significant	2 feet — ½-inch: not significant	2 feet — 2-inch: significant	2 feet — 2-inch: not significant	3 feet — Electrode diameter ½-inch: significant	3 feet — ½-inch: not significant	3 feet — 2-inch: significant	3 feet — 2-inch: not significant
40	6-12	x		x			x	x	
	6-24		x	1/			x		x
	6-36	x		x			x	x	
	12-24	x		1/			x		x
	12-36		x	x		1/		x	
	24-36	x			x	1/			x
60	6-12	1/			x		x	x	
	6-24	1/			x		x		x
	6-36	1/			x		x		x
	12-24		x		x		x		x
	12-36		x	x		x			x
	24-36		x	x		x			x
90	6-12		x	1/			x		x
	6-24		x		x		x	x	
	6-36		x		x		x	1/	
	12-24		x	1/			x		x
	12-36		x	1/			x	1/	
	24-36		x		x	x		1/	

1/ Control tests not uniform. No test for significance.

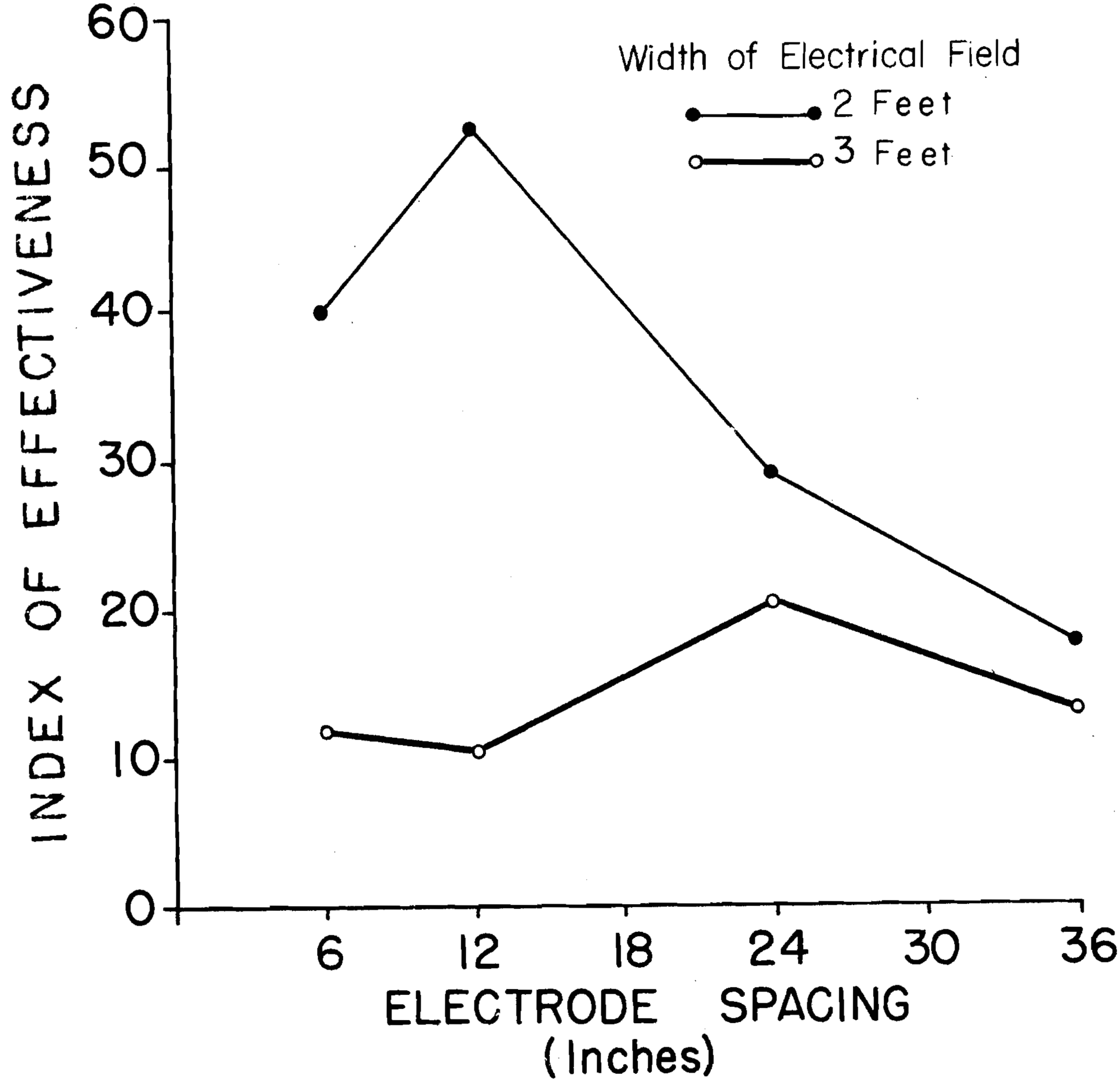

Figure 5.--The effect of electrode spacing in relation to the width of electrical field using ½-inch electrodes at a 40° angle of electrical field with a voltage gradient of 1 volt/cm., a pulse frequency of 8 pulses/sec., a pulse duration of 40 milliseconds, and a square wave form.

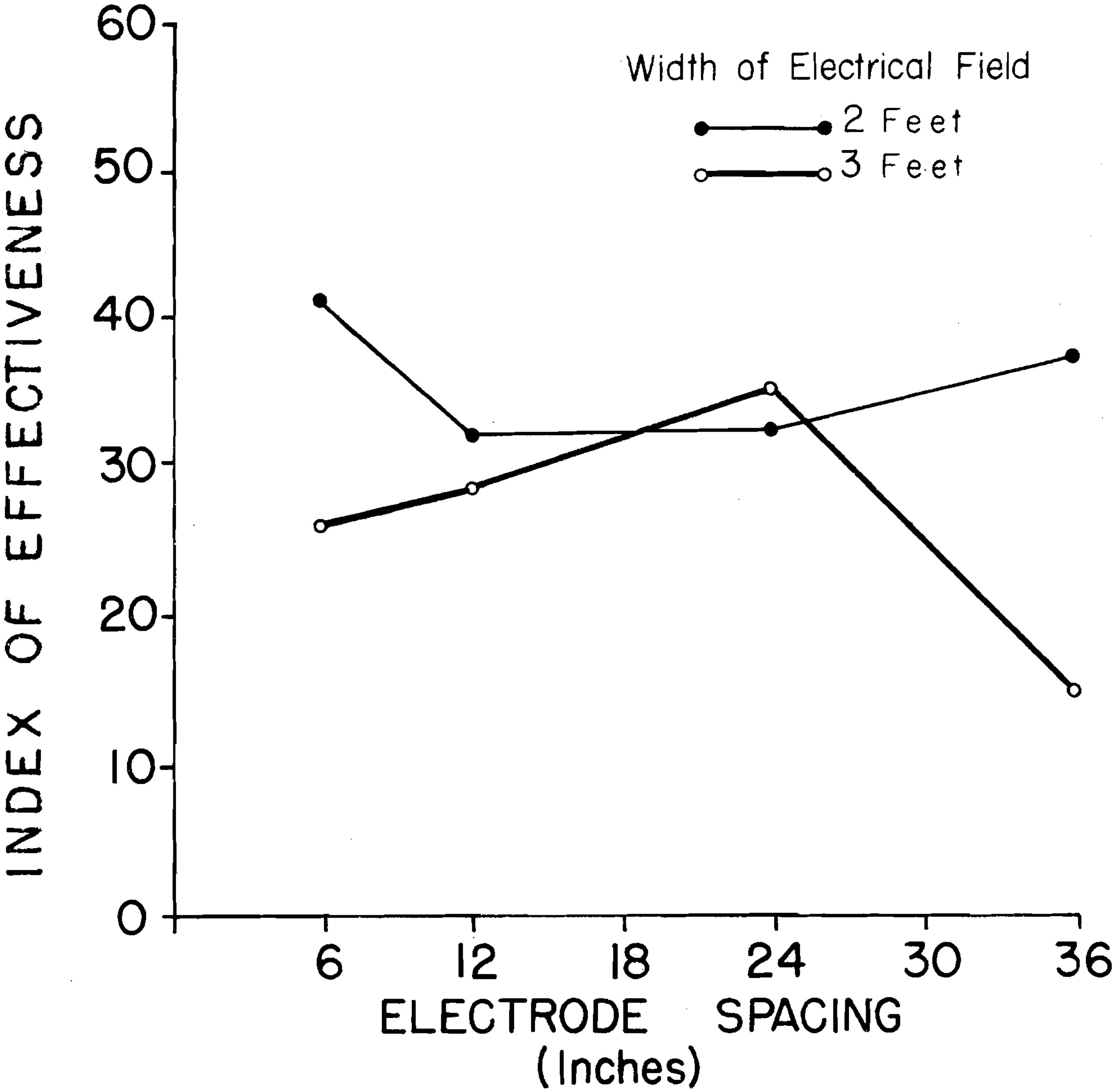

Figure 6 --The effect of electrode spacing in relation to the width of electrical field using ½-inch electrodes at a 60° angle of electrical field with a voltage gradient of 1 volt/cm., a pulse frequency of 8 pulses/sec., a pulse duration of 40 milliseconds, and a square wave form.

When the angle was increased to 90° the 2-foot width of electrical field appeared to be consistently more effective than the 3-foot field (fig. 7). The maximum difference in effectiveness occurred at an electrode spacing of 24 inches.

The results when 2-inch electrodes were substituted for 1/2-inch electrodes showed a decrease in the difference of effectiveness between the 2- and 3-foot widths of electrical field. At a 90° angle of electrical field the 2-foot width was more effective than the 3-foot width of field; the greatest difference occurred at a 24-inch electrode spacing (fig. 8).

The effect of the angle of field is shown in Figures 9 and 10. There appears to be little difference in the effectiveness of the 40° and 60° angles of field with two exceptions. One exception occurs at a 12-inch electrode spacing, 2-inch electrodes and a 2-foot width of electrical field; at this point the maximum percentage of fingerlings was effected. Another exception occurs at a 6-inch spacing, 2-inch electrodes and a 3-foot width of field; the effectiveness is considerably less than the maximum effectiveness but a significant difference exists between the 40° and 60° angles of field. The 90° angle appears to be the least effective of the three angles of field.

At a 40° angle with 1/2-inch electrodes and a 2-foot width of field the effectiveness of electrode spacing increased between 6 and 12 inches and decreased to a spacing of 36 inches (fig. 11). There appeared to be only a slight difference of effectiveness at the 60° and 90° angles of field. An increase in the width of field to 3 feet and in the diameter of the electrodes to 2 inches showed a similar result for the same angles (fig. 12).

There appears to be only a slight difference in effectiveness between 1/2-inch and 2-inch diameter electrodes. At a 40° angle of field and a 2-foot width of field a significant difference exists between the two diameters at a 6-inch electrode spacing (fig. 13). When the width of field was increased to 3 feet, the difference in effectiveness was greater at a closer electrode spacing (fig. 14). At a 90° angle of field the difference in effectiveness increases between an electrode spacing of 6 and 24 inches and decreases at a 36-inch spacing (fig. 15).

Preliminary tests were run under a maximum light intensity to investigate the effect of light on the effectiveness. In one test the previously described procedure was followed in which 60 fingerlings were released. At an angle of 40°, electrode spacing 6 inches, a width of field of 2 feet and with 1/2-inch electrodes a slight increase occurred. When 200 fingerlings were released the effectiveness was again increased.

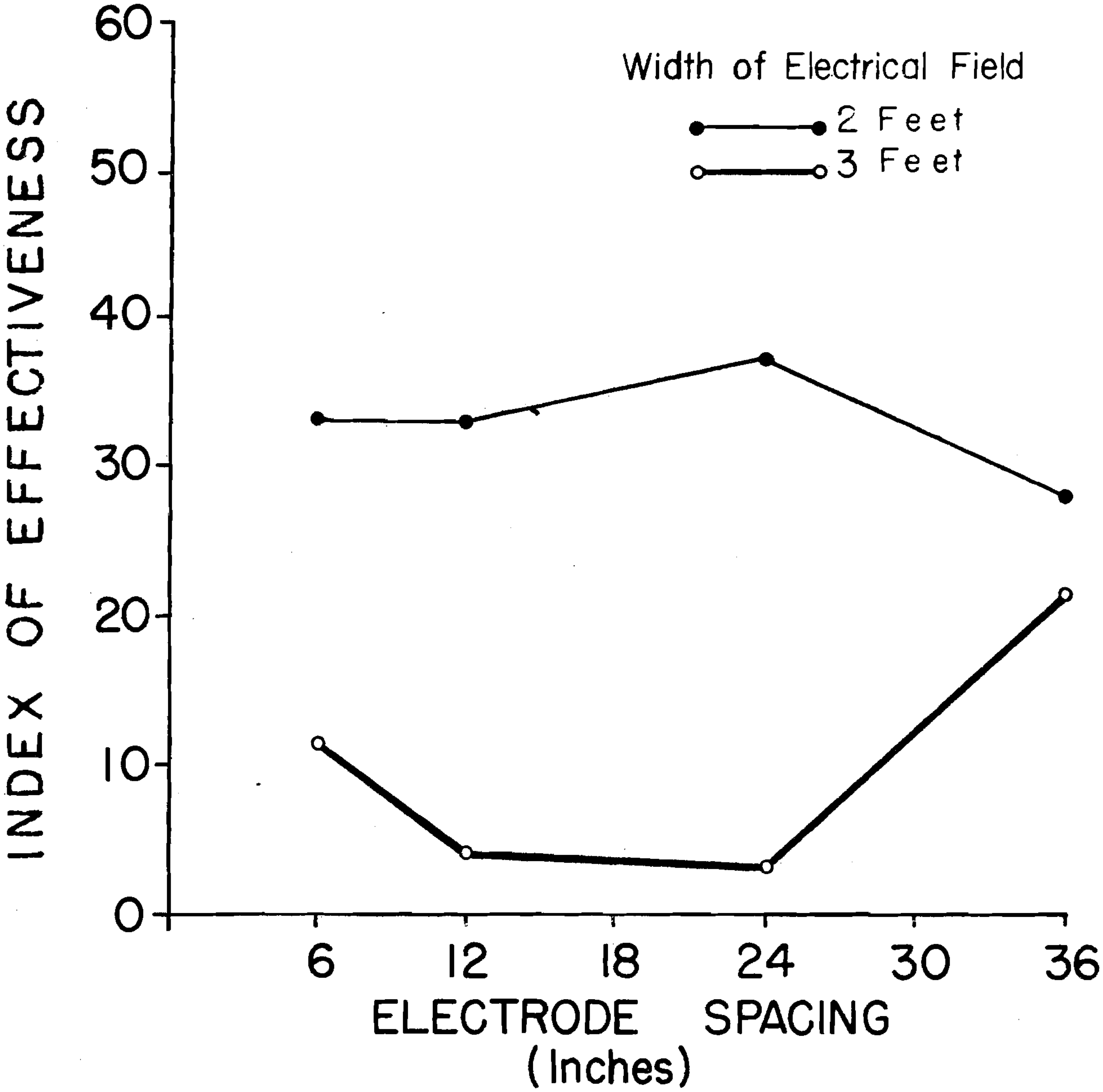

Figure 7.--The effect of electrode spacing in relation to the width of electrical field using ½-inch electrodes at a 90° angle of electrical field with a voltage gradient of 1 volt/cm., a pulse frequency of 8 pulses/sec., a pulse duration of 40 milliseconds, and a square wave form.

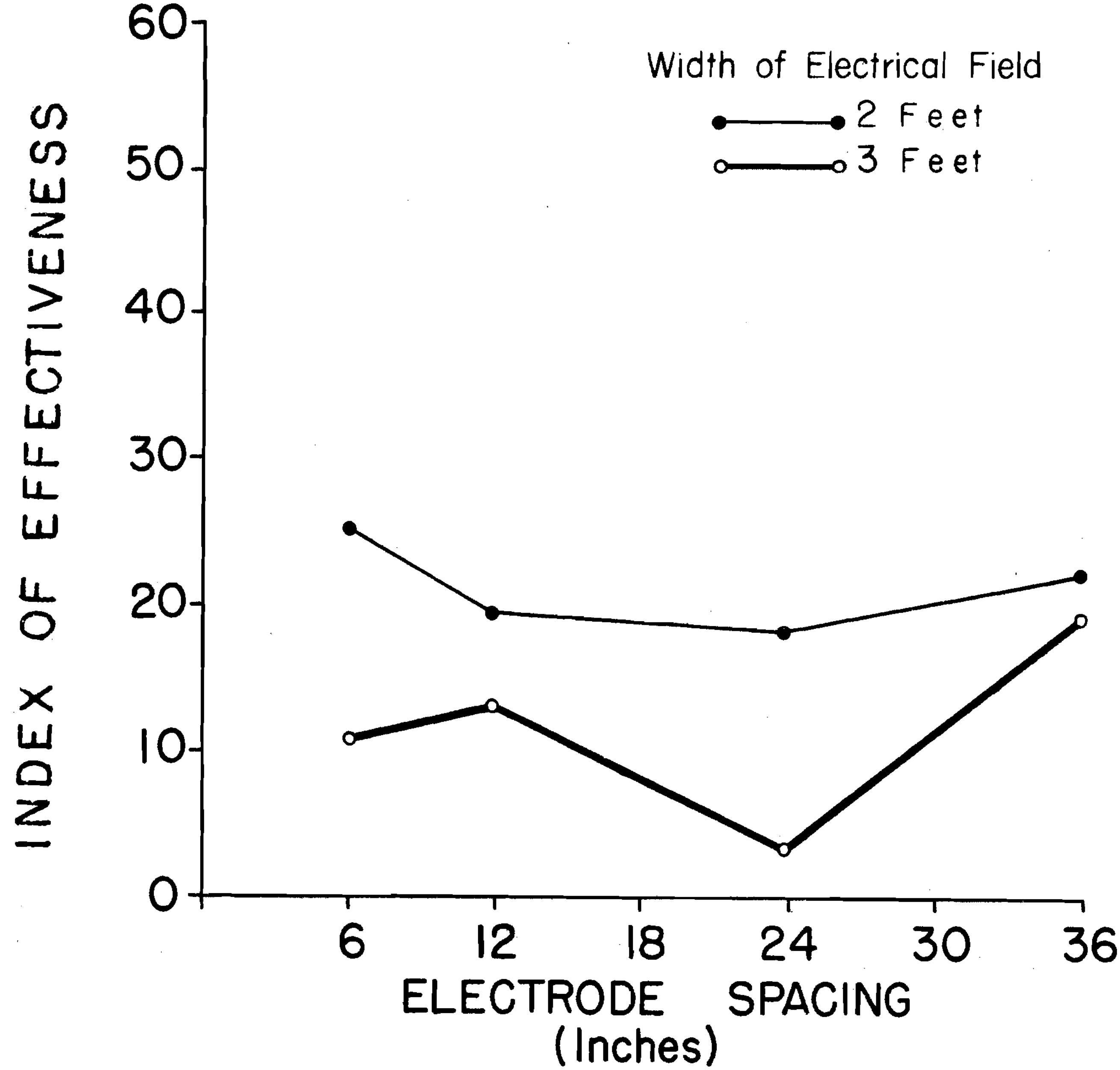

Figure 8.--The effect of electrode spacing in relation to the width of electrical field using 2-inch electrodes at a 90° angle of electrical field with a voltage gradient of 1 volt/cm., a pulse frequency of 8 pulses/sec., a pulse duration of 40 milliseconds, and a square wave form.

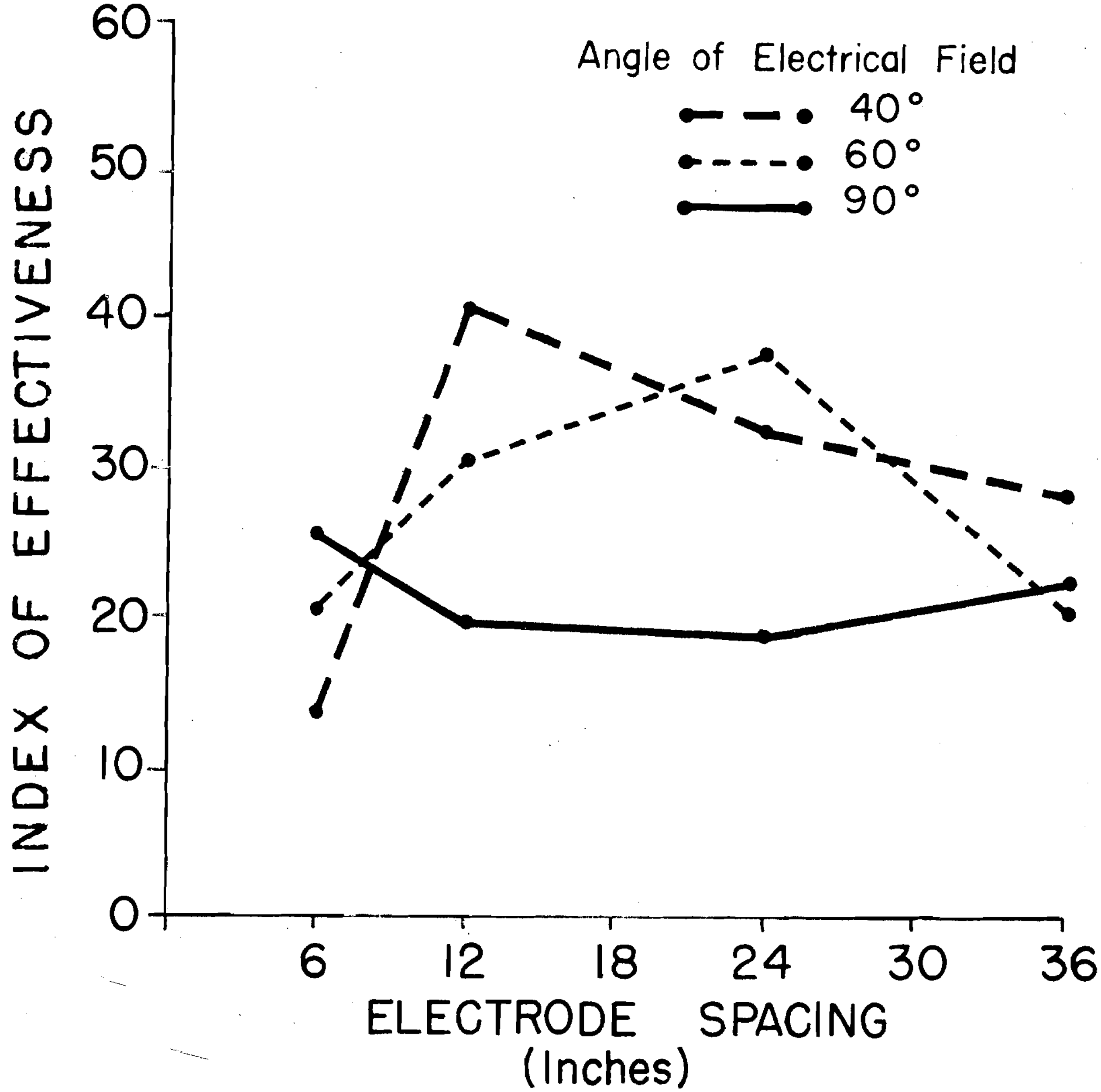

Figure 9.--The effect of electrode spacing in relation to the angle of electrical field using 2-inch electrodes at a width of electrical field of 2 feet with a voltage gradient of 1 volt/cm., a pulse frequency of 8 pulses/sec., a pulse duration of 40 milliseconds, and a square wave form.

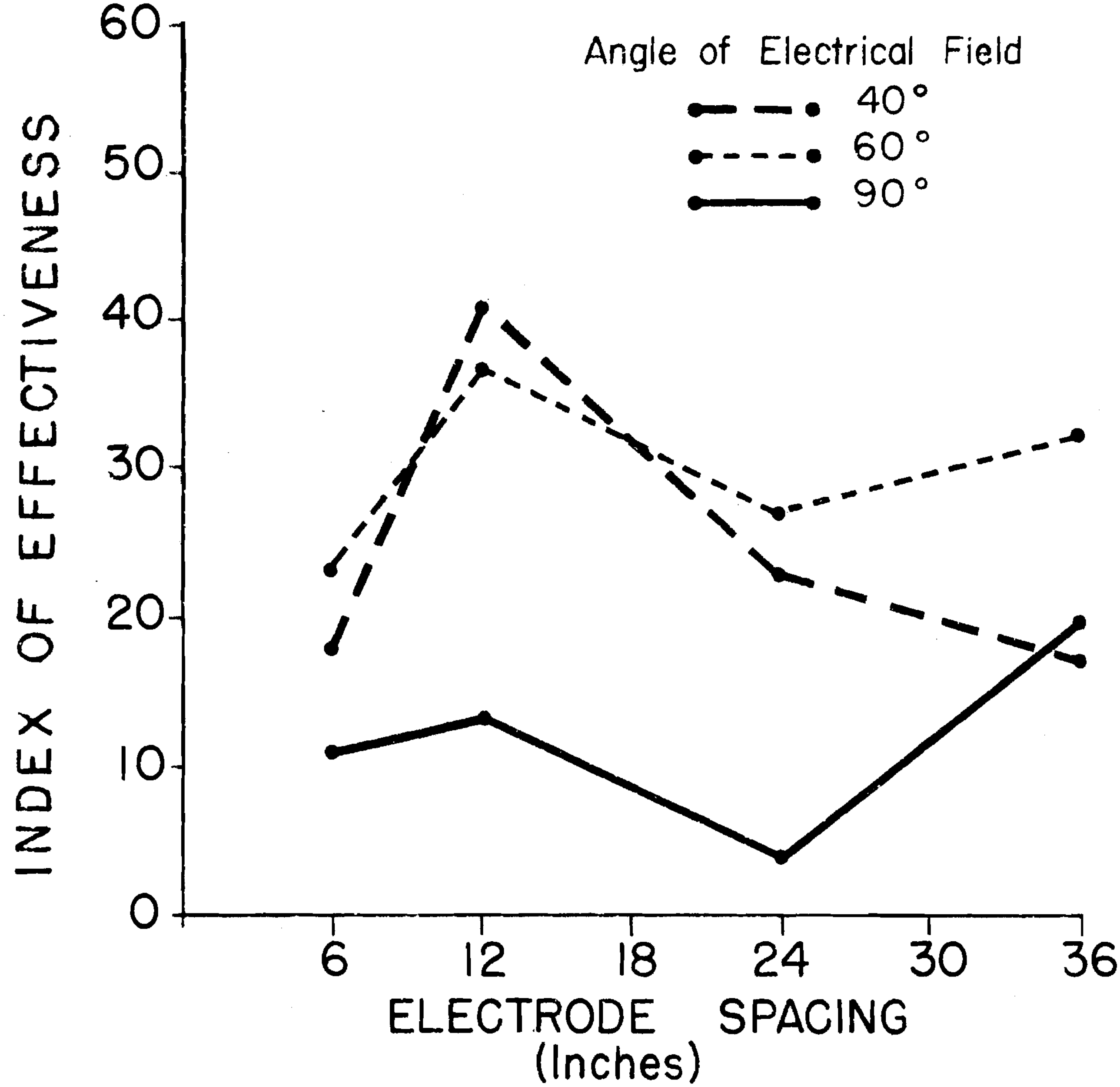

Figure 10.--The effect of electrode spacing in relation to the angle of electrical field using 2-inch electrodes at a width of electrical field of 3 feet with a voltage gradient of 1 volt/cm., a pulse frequency of 8 pulses/sec., a pulse duration of 40 milliseconds, and a square wave form.

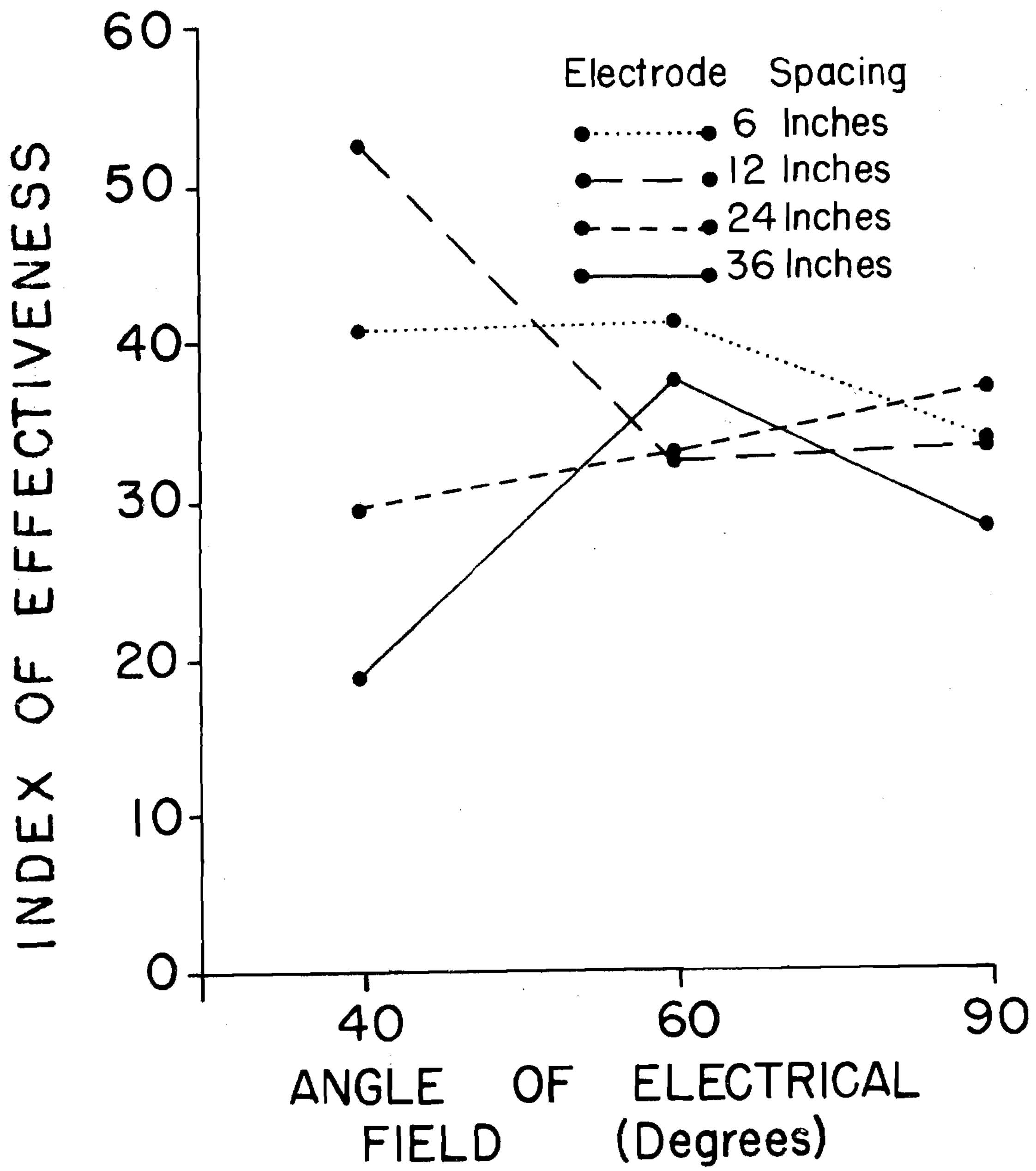

Figure 11.--The effect of the angle of electrical field in relation to electrode spacing using ½-inch electrodes at a width of electrical field of 2 feet with a voltage gradient of 1 volt/cm., a pulse frequency of 8 pulses/sec., a pulse duration of 40 milliseconds, and a square wave form.

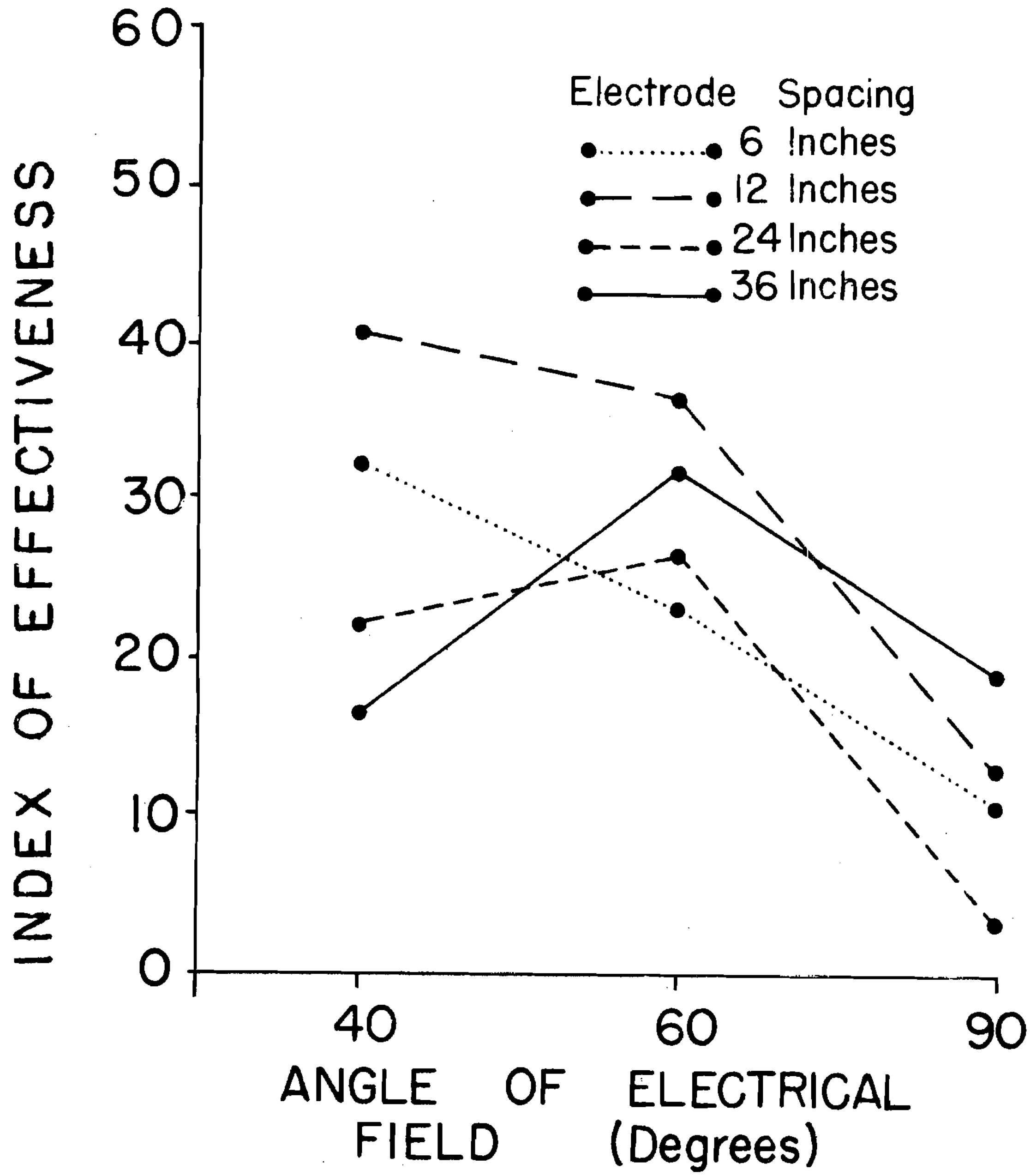

Figure 12.--The effect of the angle of electrical field in relation to electrode spacing using 2-inch electrodes at a width of electrical field of 3 feet with a voltage gradient of 1 volt/cm., a pulse frequency of 8 pulses/sec., a pulse duration of 40 milliseconds, and a square wave form.

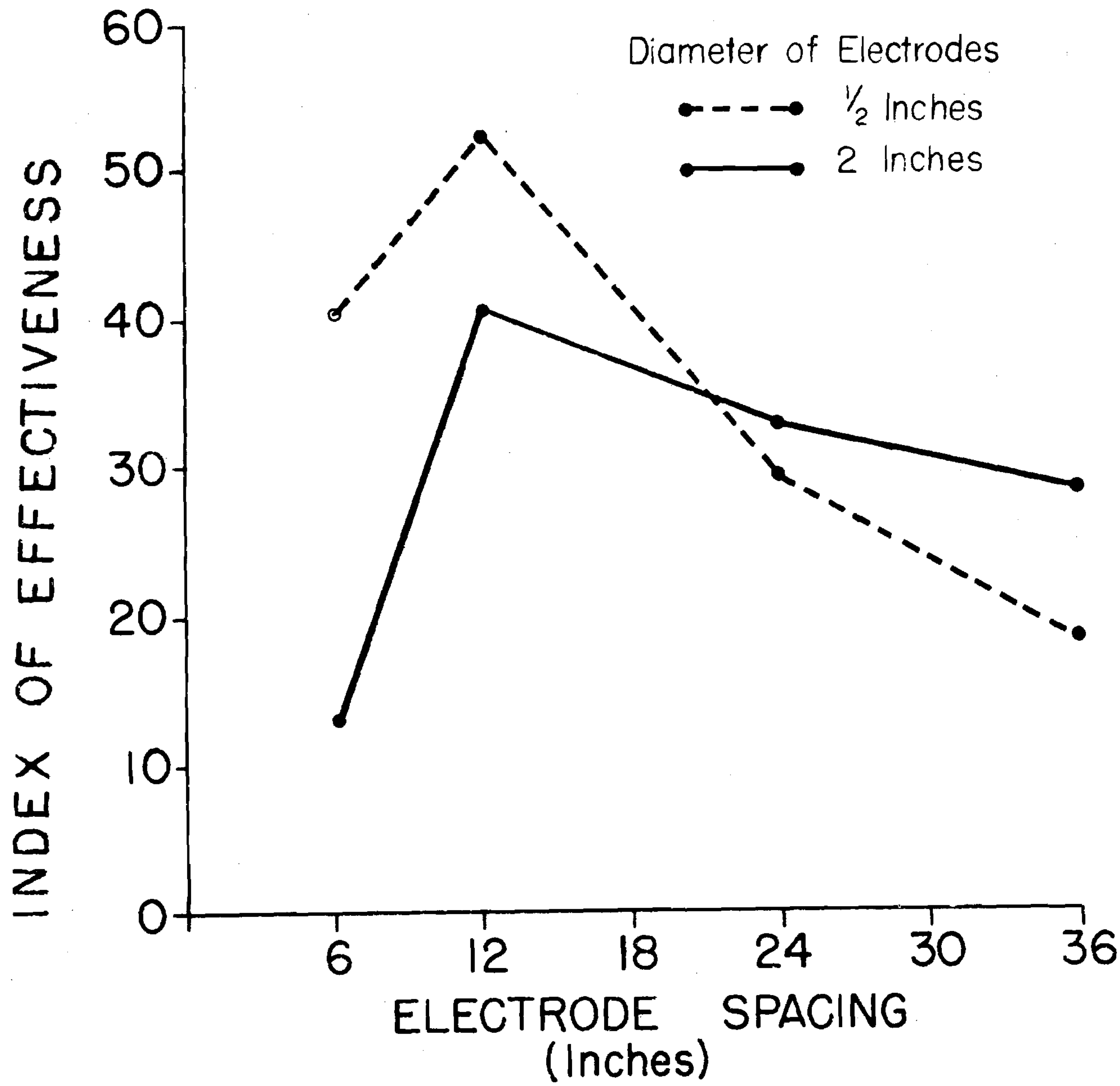

Figure 13.--Effect of electrode spacing in relation to electrode diameter using a width of electrical field of 2 feet at a 40° angle of electrical field with a voltage gradient of 1 volt/cm., a pulse frequency of 8 pulses/sec., a pulse duration of 40 milliseconds, and a square wave form.

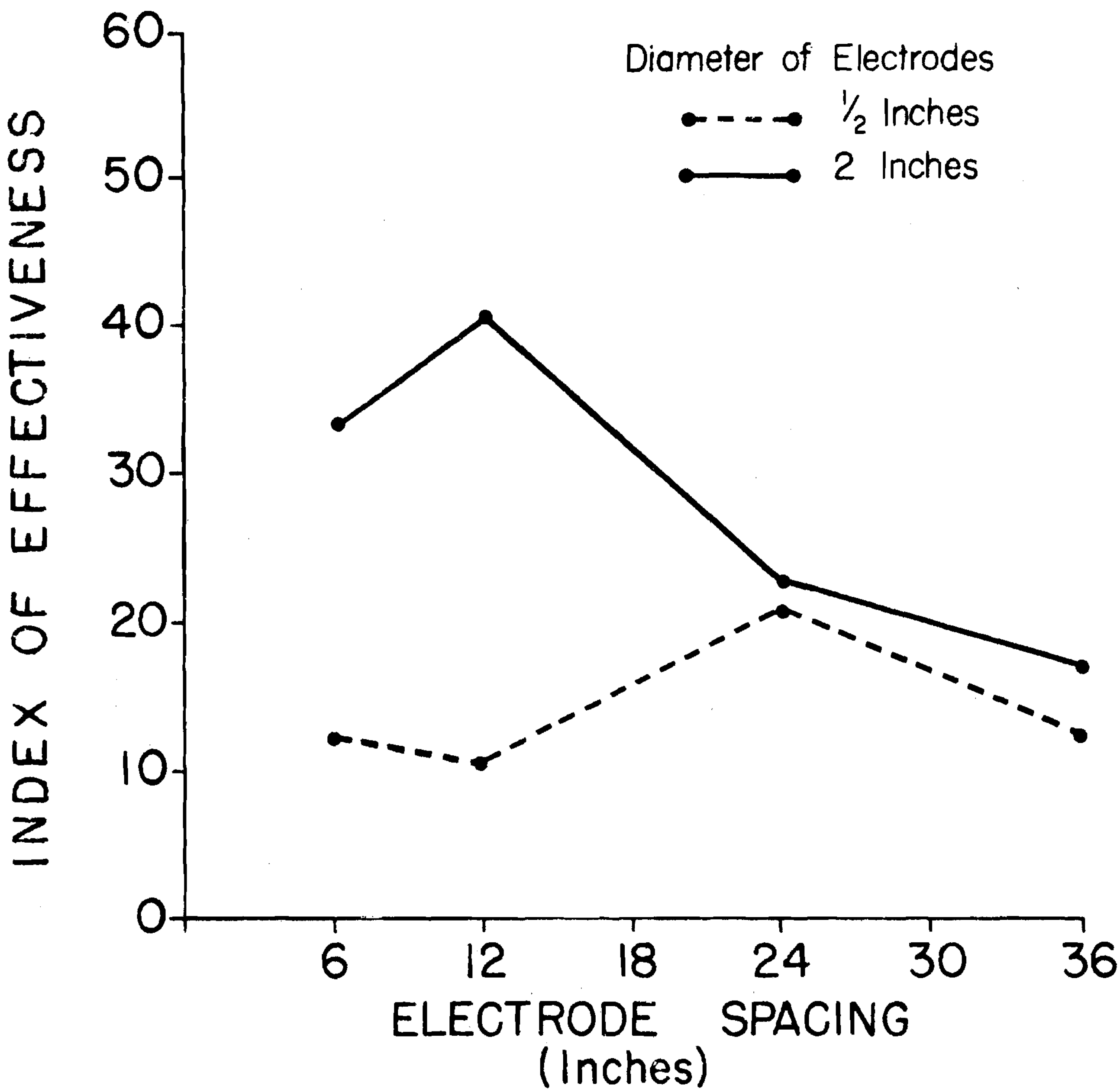

Figure 14.--Effect of electrode spacing in relation to electrode diameter using a width of electrical field of 3 feet at a 40° angle of electrical field with a voltage gradient of 1 volt/cm., a pulse frequency of 8 pulses/sec., a pulse duration of 40 milliseconds, and a square wave form.

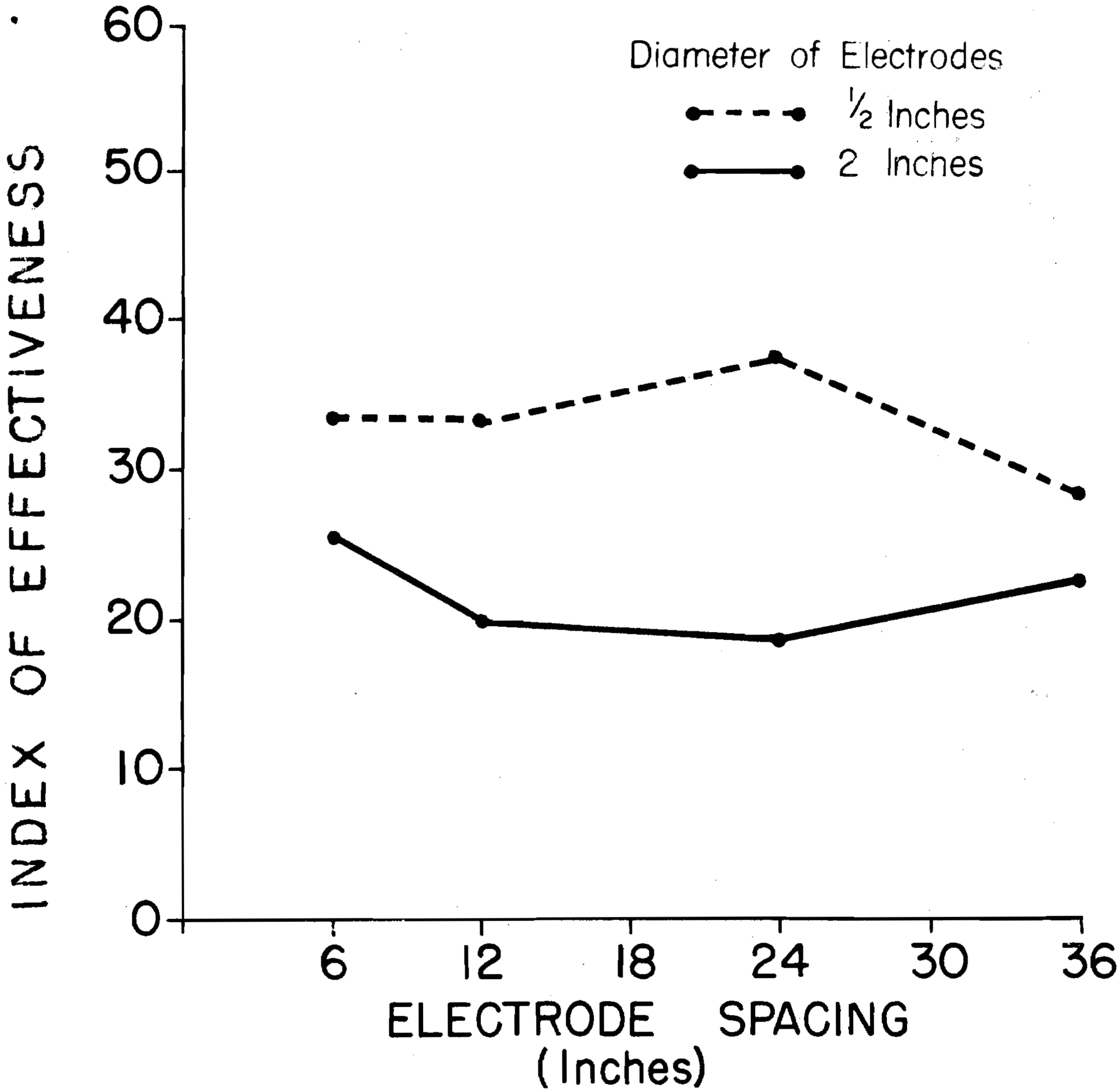

Figure 15.--Effect of electrode spacing in relation to electrode diameter using a width of electrical field of 2 feet at a 90° angle of electrical field with a voltage gradient of 1 volt/cm., a pulse frequency of 8 pulses/sec., a pulse duration of 40 milliseconds, and a square wave form.

Table 13. Effect of Electrode Spacing on the Index of Effectiveness in Relation to the Width of Electrical Field at a 40° Angle of Electrical Field with 1/2-inch Electrodes

Electrode spaces (inches)	Width of Electrical Field: 2 feet — Total No. collected in traps 1/	2 feet — % Collected in narrow channel after electrical tests	2 feet — % Collected in narrow channel after control tests	2 feet — Index of effectiveness	3 feet — Total No. collected in traps 1/	3 feet — % Collected in narrow channel after electrical tests	3 feet — % Collected in narrow channel after control tests	3 feet — Index of effectiveness
6	102	72.5	31.9	40.6	132	38.6	26.6	12.6
12	100	68.0	15.6	52.4	124	37.9	27.7	10.2
24	131	58.0	28.8	29.2	118	41.5	21.0	20.5
36	126	46.0	27.3	18.7	100	42.0	29.4	12.6 2/

1/ A total of 120 fingerlings were released for each test condition. Fingerlings not collected in traps were forced upstream of the experimental area before subsequent tests.

2/ These tests discarded; respective control tests not uniform.

Table 14. Effect of Electrode Spacing on the Index of Effectiveness in Relation to the Width of Electrical Field at a 40° Angle of Electrical Field with 2-inch Electrodes

Electrode spacing (inches)	Width of Electrical Field: 2 feet — Total No. collected in traps 1/	2 feet — % Collected in narrow channel after electrical tests	2 feet — % Collected in narrow channel after control tests	2 feet — Index of effectiveness	3 feet — Total No. collected in traps 1/	3 feet — % Collected in narrow channel after electrical tests	3 feet — % Collected in narrow channel after control tests	3 feet — Index of effectiveness
6	140	46.4	33.0	13.4	125	51.2	33.2	18.0
12	115	66.1	25.2	40.9	109	57.8	17.1	40.7
24	104	58.6	26.0	32.6 2/	108	45.4	22.8	22.6
36	120	45.8	17.6	28.2	117	37.6	20.7	16.9

1/ A total of 120 fingerlings were released for each test condition. Fingerlings not collected in traps were forced upstream of the experimental area before subsequent tests.

2/ These tests discarded; respective control tests not uniform.

Table 15. Effect of Electrode Spacing on the Index of Effectiveness in Relation to the Width of Electrical Field at a 60° Angle of Field with 1/2-inch Electrodes

	Width of Electrical Field							
	2 feet				3 feet			
Electrode spacing (inches)	Total No. collected in traps 1/	% Collected in narrow channel after electrical tests	% Collected in narrow channel after control tests	Index of effectiveness	Total No. collected in traps 1/	% Collected in narrow channel after electrical tests	% Collected in narrow channel after control tests	Index of effectiveness
6	111	68.5	27.3	41.2 2/	95	49.5	23.1	26.4
12	134	55.2	23.0	32.2	102	57.8	29.0	28.8
24	110	54.5	21.6	32.9	93	60.2	24.6	35.6
36	118	54.2	16.7	37.5	100	41.0	25.9	15.1

1/ A total of 120 fingerlings were released for each test condition. Fingerlings not collected in traps were forced upstream of the experimental area before subsequent tests.

2/ These tests discarded; respective control tests not uniform.

Table 16. Effect of Electrode Spacing on the Index of Effectiveness in Relation to the Width of Electrical Field at a 60° Angle of Electrical Field with 2-inch Electrodes

Electrode spacing (inches)	Width of Electrical Field: 2 feet				Width of Electrical Field: 3 feet			
	Total No. collected in traps 1/	% Collected in narrow channel after electrical tests	% Collected in narrow channel after control tests	Index of effectiveness	Total No. collected in traps 1/	% Collected in narrow channel after electrical tests	% Collected in narrow channel after control tests	Index of effectiveness
6	124	43.5	22.7	20.8	130	46.2	23.1	23.1
12	130	66.9	26.1	40.8	102	58.8	22.3	36.5
24	117	57.3	19.6	37.7	106	49.1	22.2	26.9
36	111	42.3	21.7	20.6	108	49.1	27.1	22.0

1/ A total of 120 fingerlings were released for each test condition. Fingerlings not collected in traps were forced upstream of the experimental area before subsequent tests.

2/ These tests discarded; respective control tests not uniform.

Table 17. Effect of Electrode Spacing on the Index of Effectiveness in Relation to the Width of Electrical Field at a 90° Angle of Electrical Field with 1/2-inch Electrodes

	Width of Electrical Field							
	2 feet				3 feet			
Electrode spacing (inches)	Total No. collected in traps 1/	% Collected in narrow channel after electrical tests	% Collected in narrow channel after control tests	Index of effectiveness	Total No. collected in traps 1/	% Collected in narrow channel after electrical tests	% Collected in narrow channel after control tests	Index of effectiveness
6	83	56.6	22.8	33.8	100	32.0	20.1	11.9
12	108	50.9	17.8	33.1	104	31.7	27.5	4.2
24	105	56.2	18.9	37.3	140	25.0	21.7	3.3
36	124	47.6	19.4	28.2	119	42.9	21.3	21.6

1/ A total of 120 fingerlings were released for each test condition. Fingerlings not collected in traps were forced upstream of the experimental area before subsequent tests.

2/ These tests discarded; respective control tests not uniform.

Table 18. Effect of Electrode Spacing on the Index of Effectiveness in Relation to the Width of Electrical Field at a 90° Angle of Electrical Field with 2-inch Electrodes

Electrode spacing (inches)	Width of Electrical Field: 2 feet — Total No. collected in traps 1/	2 feet — % Collected in narrow channel after electrical tests	2 feet — % Collected in narrow channel after control tests	2 feet — Index of effectiveness	3 feet — Total No. collected in traps 1/	3 feet — % Collected in narrow channel after electrical tests	3 feet — % Collected in narrow channel after control tests	3 feet — Index of effectiveness
6	106	40.6	15.0	25.6	114	36.8	25.7	11.1
12	114	39.5	19.7	19.8	119	32.8	19.8	13.0
24	120	41.7	23.1 2/	18.6	124	24.2	20.5	3.7
36	109	38.5	16.1	22.4	109	39.4	20.2	19.2 2/

1/ A total of 120 fingerlings were released for each test condition. Fingerlings not collected in traps were forced upstream of the experimental area before subsequent tests.

2/ These tests discarded; respective control tests not uniform.

DISCUSSION

The results of these exploratory experiments generally agree with the results of other investigators. Lethlean (1953) noted that he expected better results by increasing the angle of the lines of electrodes in relation to the dam from 30° to 45°. Biologists of the International Pacific Salmon Fisheries Commission were quite successful at Cultus Lake (1953) in diverting salmon fingerlings with an angle of 45° and a 2-foot width of field.

In the experiments under the laboratory conditions described, a maximum percentage was recovered in the narrow channel with the rows of electrodes spaced 2 feet apart. When the width of field was increased to 3 feet the effectiveness was reduced and it was observed that many fish experienced difficulty in escaping an area in the immediate vicinity of a positive electrode. At the same time other fish were paralyzed in the electrical field and were carried through it by the water current until they recovered equilibrium beyond the field. These factors are probably the cause of much of the scatter in the data resulting from the 3-foot width of field; they are possibly the result of the increased power necessary to maintain the average voltage gradient of 1 volt/cm. McMillan (1928) pointed out that when the distance between rows of electrodes was increased while maintaining a constant voltage gradient the concentration of the voltage gradient at the surface of the electrodes increased.

Tests run under full light intensity resulted in a slight increase of the effectiveness. A further increase was obtained when large numbers were released under full light intensity. The results of these preliminary experiments suggest that group movement may be an important factor in diverting salmon fingerlings. When large schools migrate downstream into an electrical field the effectiveness may be higher than when smaller groups come in contact with d.c. barrier. Okada (1929) observed that a weaker field can restrain the same percentage of fish as a stronger one when the group was composed of many fish, indicating that group movement was involved in his experiments.

Since full-scale field trials were scheduled to begin subsequent to the completion of these laboratory experiments, the experiments were limited to three angles, two diameters of electrodes, a single field, and one arrangement of electrodes. The experiments were conducted within a range of temperatures of 8°C., with a maximum temperature of 16°C. Two test and two control experiments were used to investigate any one set of conditions; each point on the preceding graphs was established with approximately 100 fish. Hatchery-reared silver salmon ranging in size from 5.5 cm. to 12.0 cm. were used; this does not include the range of sizes or species that would be encountered under natural conditions. Another factor to be considered is that wild fish may be more or less sensitive to an electrical field than hatchery-reared fish. However, the experiments show the relative effectiveness of the various factors examined in this type of narrow d.c. field employed as a diverting barrier.

The results of the experiments indicated that with few exceptions the difference in the effectiveness of the 40° and 60° angles of electrical field were not significant; this was also true for 1/2-inch and 2-inch electrode diameters. There is a question of whether the size of the experimental area was large enough to allow a valid comparison of these factors. The effectiveness of the two angles of field and the two diameters of electrodes should be examined under field conditions. If this lack of significant difference is verified in the field, a considerable saving can be realized in the cost of installation and operation by establishing a 60° angle and using 1/2-inch electrodes. However, it is recognized that the effectiveness of the angle of electrical field may be a function of water velocity, numbers of fish or species of fish. These factors should be examined and the relationship to the effectiveness determined.

Since some of the fish experienced difficulty in escaping an area in the vicinity of the positive electrodes of a single d.c. field, experiments are in progress to examine the effectiveness of multiple fields of increasing intensity. A pulsating direct current of a higher intensity is necessary to divert fingerlings than is required for larger fish. By creating a zone of low intensity upstream the large fish may be diverted without injury before they reach the zone of higher intensity necessary to divert fingerlings.

During the experiments it was observed that the fingerlings entered the electrical field and oriented to the positive electrodes before they were diverted. An investigation is in progress to explore the effectiveness of a single line of electrodes with an electrical field of high intensity in an effort to divert the fingerlings before they reach the barrier. Additional tests are planned to investigate the result when the electrodes are energized sequentially.

SUMMARY

1. Exploratory experiments were completed under laboratory conditions using lines of vertically suspended electrodes with the positive line of electrodes parallel to and upstream of the negative line of electrodes and placed at an angle to flowing water.

2. The electrodes were energized with interrupted direct current of a square wave form with the following electrical characteristics: (1) a pulse frequency of 8 pulses per second, (2) a pulse duration of 40 milliseconds, and (3) an average voltage gradient of 1 volt per centimeter.

3. Hatchery-reared silver salmon ranging in size from 5.5 cms. to 12.0 cms. were used in the experiments.

4. Tests were run at a minimum level of light intensity to eliminate schooling and group movements. The technique of manipulating the light intensity stimulated downstream movement eliminating the necessity of startling or forcing the fish into the electrical field.

5. The most effective results from the laboratory experiments were obtained at an angle of 40°, a width of field of 2 feet, an electrode spacing of 12 inches with 1/2-inch diameter electrodes. Under these conditions 68 percent of the fish were directed to the collecting channel, as compared with only 16 percent in control tests with power off.

6. The 2-foot width of electrical field appeared to be more effective than the 3-foot width of field.

7. With a few exceptions the effectiveness of the 40° and 60° angles of electrical field were not significantly different. The 90° angle of field was least effective.

8. There were few significant differences between 1/2-inch and 2-inch diameter electrodes.

9. Electrode spacing appeared to be more important at a 40° angle of electrical field, than at 60° and 90°.

10. Light intensity may increase the percentage diverted through the effect on schooling behavior and group movement.

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