INTERNATIONAL PACIFIC SALMON
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PROGRESS REPORT

NO. 2

ELECTRIC SCREENS FOR ADULT SALMON

BY

F. J. ANDREW, P. C. JOHNSON and L. R. KERSEY

NEW WESTMINSTER, B.C.
CANADA
1956

INTERNATIONAL PACIFIC SALMON
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ABSTRACT

Tests were conducted in Sweltzer Creek at Cultus Lake, B.C. in 1953 to investigate the effectiveness of certain types of electric screens for deflecting and guiding adult sockeye and pink salmon. The electric screens tested consisted of two parallel rows of 1-inch diameter vertical electrodes energized with direct, interrupted direct, 60-cycle alternating, and half- and full-wave rectified alternating current. These electric screens were effective in stopping the fish provided the electrical stimuli caused a sufficient impairment of the fishes' swimming ability and the water velocity exceeded 2.0 feet per second. In lower water velocities, some fish were killed even when the galvanotropic stimuli were used. A distinct disadvantage of the electric screens tested was that fish made repeated efforts to penetrate the electrified zone rather than lead along it to a by-pass. The fish also seemed to become fatigued after repeated electrical exposures.

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ELECTRIC SCREENS FOR ADULT SALMON

INTRODUCTION

The adverse effect of dams on salmon fisheries resources has been clearly demonstrated by serious declines or even extermination of certain salmon populations in areas where dams obstruct the passage of fish either to or from their spawning grounds. Although various kinds of elevating systems for passing adult salmon are now in use at many dams, the majority of these facilities are not entirely adequate. Considerable damage is sometimes imposed on a proportion of the fish and some are killed when they try to penetrate the spillway area or enter the draft tubes because they cannot readily locate the entrance to fish-passage facilities.

Actively migrating adult salmon exhibit a strong tendency to swim against the main flow in a stream and usually avoid side channels. At a dam therefore, they are attracted by the high flows from the spillway and turbines and penetrate these to their maximum ability. The violent turbulence and upwelling below turbine draft tubes is an artificial condition that disorients the fish and probably fatigues them and delays their upstream migration. If the entrances to the fish facilities can be located at the boundaries of impassable high-velocity discharges as they are at the Hell's Gate fishways, the fish will be guided to these entrances with a minimum of delay. However, since spillway and turbine discharges fluctuate over wide limits it is frequently impossible to maintain high-velocity discharges in the correct positions for leading the fish to the by-pass facilities. It would therefore be advantageous to have other methods of directing the fish to desired locations below dams.

In the past a number of experimenters have used electrical stimuli in attempting to control the upstream migrations of adult salmon. Some of these attempts appeared to have been successful but for various reasons electric screens are not widely used at the present time. Holmes (1948) reports that the earliest application of an electric screen for stopping adult salmon was a test installation in the tailrace of the Gold Ray power plant on the Rogue River in Oregon in 1928. Local sportsmen insisted that this screen be permanently removed because many dead fish had been seen in the river below the power plant. The experimenters, however, believed that the electric screen installation was successful and that the fish had been killed by a high-voltage short-circuit through the river caused by a break in the power company's transmission lines. Another application of an adult electric screen was at a counting weir in the Kvichak River in Alaska in 1932. Another experimental electric screen was installed in the Green River in Washington in 1930 and although it blocked the upstream passage of adult salmon in the Green River, the installation was unsuccessful because, after finding their passage blocked, the fish did not migrate up Soos Creek, a tributary of Green River at the experimental site. One electric screen operating at the present time is used for diverting fish from the Entiat River in Washington to hatchery holding ponds. In all installations mentioned, alternating current was used to energize the electrodes.

Holmes also described other types of electrical stimuli that had been tried. In 1942 on Mill Creek in California, tests were conducted to determine the efficiency of high-voltage condenser discharge impulses for stopping the fish. These condenser discharges were not satisfactory as many fish escaped through the electrified area in these tests. In a more recent report, Lethlean (1953) described an electric screen that was installed across the tailrace of a hydroelectric plant in Scotland. Pulsed rectified alternating current was used to energize two rows of electrodes in such a manner as to cause successive electric fields to intersect between the two rows of electrodes. This electric screen was reported to be 100 per cent efficient for stopping the upstream migration of salmon and sea-trout.

Since electric screens appeared to have been successful, in some instances, for stopping the upstream migration of adult salmon, and since galvanotropic screens appeared to be effective for guiding downstream-migrant sockeye under certain conditions (Andrew, Kersey and Johnson, 1955), it was decided that experiments should be conducted to further investigate the possible effectiveness of electric screens for guiding adult salmon.

PRELIMINARY LABORATORY EXPERIMENTS

In July, 1953, a series of preliminary experiments was conducted with adult sockeye at Baker Dam in Washington to obtain information required for the design of a field experiment. It was considered that a galvanotropic stimulus that had been effective for guiding downstream-migrant sockeye in small-scale experiments at Cultus Lake might also be effective for guiding adult sockeye. However, no information was available to indicate whether adult sockeye would exhibit a galvanotropic reaction or what electrical conditions might be required.

The experiments were conducted in small wooden tanks using both direct and interrupted direct current. Direct current was obtained from a 1.5-kilowatt compound-wound generator. A rotating switch, operated by a variable-speed direct current motor, was used for interrupting the direct current and for controlling the frequency and duty cycle. Voltage was measured on a cathode-ray oscillograph. There was virtually no commutator ripple in the output of the generator.

The fish were obtained from a holding tank at the crest of Baker Dam after being hauled by an aerial cableway from the trapping facilities at the tailrace of the power plant. The 40 male and 45 female sockeye used in these experiments appeared to be in good condition. The average fork length of the males was 25.4 inches (range 28.6 to 22.8 inches) and of the females was 23.8 inches (range 27.6 to 21.5 inches). The specific resistance of the water in the forebay of the dam was about 16,500 ohms per inch-cube but for certain experiments the specific resistance was decreased by the addition of sodium chloride to the water.

The first phase of the preliminary experiment was the determination of threshold voltage gradients. Adult sockeye were placed in a rectangular wooden trough, 89 inches long, 10 inches wide, and 12 inches deep, with a water depth of about 10 inches. Galvanized wire screen electrodes were placed at both ends. Fish were aligned at right angles to the electrodes and the total voltage across the electrodes was raised in one-volt increments until a response was noted. The threshold value was considered to be the minimum gradient (total applied voltage divided by the distance between electrodes) required to produce a pronounced muscular contraction when the power was turned on. Minor reactions such as slight fin movements were disregarded. The threshold values were critical; fish remained almost motionless in the trough until a specific voltage was reached. However, it was found that immediately after having shown a response to the threshold voltage, the same fish would also respond to a slightly lower voltage but if a number of seconds elapsed between the application of the threshold and subthreshold voltages the latter had very little effect. It was important to maintain the fish in a position with its length parallel to the lines of current flow because in any other position a significantly higher voltage was required before a response was noted. A switch was incorporated in the circuit to change the polarity of the electrodes and threshold voltages were determined for each fish when facing the anode and facing the cathode. With interrupted direct current, frequencies of 0.5 to 7 pulses per second and duty cycles of 2 to 90 per cent were used.

Table 1 shows the threshold voltage gradients for direct current and various combinations of frequency and duty cycle of interrupted direct current at two different water resistivities. In these tests there was no significant difference in the threshold voltages obtained with individual fish at the

TABLE 1

VOLTAGE GRADIENTS REQUIRED FOR PRODUCING THRESHOLD RESPONSE OF ADULT SOCKEYE AT BAKER DAM, USING DIRECT CURRENT AND INTERRUPTED DIRECT CURRENT

	Length Inches	Voltage Gradient Facing Anode v/in.	Voltage Gradient Facing Cathode v/in.	Frequency pps.	Duty Cycle Per Cent	Number of Measurements
	Water resistivity 15,200 to 17,100 ohms per inch-cube. Water temperature 51°F to 54°F.					
	MALES					
	25.2	0.36	0.16	4	75	2
	25.6	0.30	0.14	4	75	2
	27.2	0.42	0.19	0-7	75 - 100	16
	27.0	0.27	0.15	0.5-7	75	14
	25.2	0.21	0.12	0.5-7	75	14
	23.8	0.26	0.14	0.5-7	75	14
	27.0	0.24	0.12	0-3	10 - 100	22
	27.0	0.22	0.13	0-3	10 - 100	22
	22.8	0.32	0.15	0-3	10 - 100	22
	26.0	0.34	0.28	0.5-7	2	14
Av.	25.7	0.29	0.16			
	FEMALES					
	23.6	0.28	0.19	4	75	2
	24.8	0.22	0.11	4	75	2
	24.8	0.26	0.14	4	75	2
	23.6	0.20	0.12	4	75	2
	21.7	0.26	0.12	0.5-6	75	10
	22.4	0.32	0.13	0.5-7	75	14
	22.4	0.20	0.13	0.5-7	75	14
	23.8	0.37	0.12	0-3	10 - 100	22
	22.6	0.35	0.14	0-3	10 - 100	12
	22.8	0.26	0.13	0-3	10 - 100	12
	23.6	0.35	0.15	0.5-7	2	16
Av.	23.3	0.28	0.13			
	Water resistivity 2,780 to 3,100 ohms per inch-cube. Water temperature 52°F to 53°F.					
	MALES					
	27.4	0.12	0.05	0-7	50 - 100	12
	27.4	0.11	0.05	3	2 - 90	12
Av.	27.4	0.11	0.05			

TABLE 1 (Cont.)

	Voltage Gradient				
Length Inches	Facing Anode v/in.	Facing Cathode v/in.	Frequency pps.	Duty Cycle Per Cent	Number of Measurements
FEMALES					
26.0	0.10	0.04	0-7	50 - 100	10
23.6	0.15	0.06	0-7	50 - 100	16
26.0	0.08	0.04	3	2 - 90	16
23.6	0.13	0.05	3	2 - 90	12
Av. 24.8	0.12	0.05			

Note: Non-interrupted direct current is indicated by a frequency of zero and by a duty cycle of 100 per cent.

different combinations of frequency and duty cycle, indicating that there was no relationship between frequency and threshold voltage nor between duty cycle and threshold voltage. Within the ranges of frequency and duty cycle used in these tests the intensity was the only factor affecting the threshold response of individual fish. These data do not indicate a relationship between threshold voltage gradient and the length of fish but it is interesting to note that the females responded to the same or a slightly lower voltage gradient than the males. The fact that the females were smaller than the males suggests that the females may be more sensitive to electrical stimuli. It is important to note that the threshold voltage gradient when fish faced the anode was approximately double that required when the fish faced the cathode.

Another experiment was conducted to determine the relationship between threshold voltage and water resistivity. The resistivity was varied from 16,500 ohms per inch-cube to 400 ohms per inch-cube and at a number of resistivity levels within this range, the anode and cathode threshold voltage gradients were measured for one male and one female. The results are shown in Figure 1. There was a progressive decrease in the voltage gradient required to produce threshold response as the resistivity of the water was decreased. For all levels of salinity used, the anode threshold voltage was approximately double the cathode threshold voltage.

An experiment was also conducted to determine whether the threshold voltage would change in relation to time if fish were immersed in water of higher salinity than that to which they had been accustomed. For this test, salt was added to the water, reducing the resistivity to 1,440 ohms per inch-cube. One fish was placed in the test trough for 40 minutes and during this time 20 threshold voltage gradients were measured. That is, 10 anode-cathode readings were taken

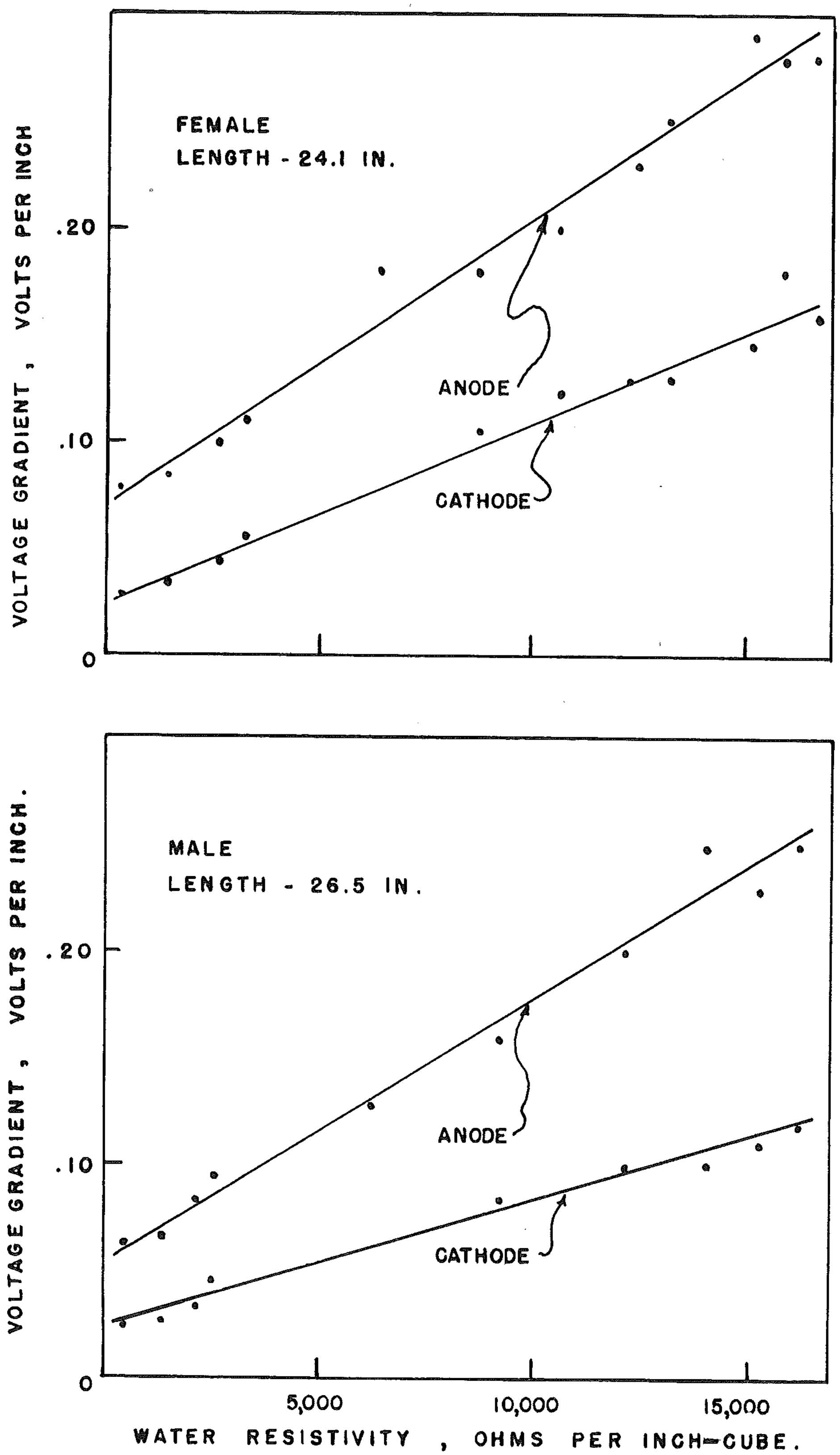

Figure 1. Relation between water resistivity and threshold voltage gradient for fish facing the anode and facing the cathode.

in a period of 40 minutes and were spaced approximately 4 minutes apart. In this interval of time the measured threshold voltage gradients were almost constant; differences in the individual readings were so slight that they could be attributed entirely to experimental error. The average of the 10 anode threshold voltage gradient readings was 0.089 volts per inch; the maximum reading was 0.096 and the minimum was 0.084. The average cathode threshold voltage gradient was 0.028; the maximum reading was 0.034 and the minimum was 0.026. The stimulus used in these tests was interrupted direct current at a frequency of 3 pulses per second and a duty cycle of 50 per cent but, as previously indicated, these relationships would apply for other interrupted direct current stimuli because neither frequency nor duty cycle appeared to have any effect on the threshold response.

To determine the effect of various interrupted direct current stimuli on immobilization, fish were electrically exposed in a trough 29 inches long and 10 inches wide with a water depth of 7 inches. They were prevented from coming in contact with the wire screen electrodes at the ends of the tank by $\frac{1}{4}$-inch mesh webbing barriers placed between the fish and the electrodes. Nine adult sockeye were chosen at random and subjected individually to various conditions of electrical stimulation. In all tests the fish were aligned perpendicular to the plane of the electrodes and facing the cathode. Water temperature was maintained almost constant at 53°F and water resistivities were 2,680 and 4,330 ohms per inch-cube. A voltage gradient of 1.235 volts per inch was used in all tests. Frequencies of 5, 8, and 10 pulses per second were used at each of the duty cycles 50, 70 and 90 per cent. Individual fish were placed in the trough and after they became quieted, the voltage was applied and observations of the activity of the fish were recorded. When the fish became immobilized, the current was turned off and the fish were allowed to regain their equilibrium. The recovery time (time required to regain equilibrium) was also recorded. Fish were prodded from time to time both before immobilization and after in order to ensure that they were not supported in a normal upright position by the bottom, walls, or ends of the enclosure. The results of these tests are shown in Table 2.

When the current was first applied, muscular contractions were quite violent and appeared to be in phase with the given frequency but as the exposure continued the contractions became less pronounced. The opercula remained closed while the current was on but resumed moving as soon as the current was turned off, slowly and indefinitely at first but gradually returning to normal. During the recovery period, fish usually made several attempts to right themselves but were not considered to have recovered until they were able to maintain a normal upright position. The results do not indicate that certain frequencies or duty cycles were more severe than others or that sexes were affected differently. All fish exposed to a voltage gradient of 1.235 volts per inch of interrupted direct current became immobilized by continued exposure but regained their equilibrium in a short time if the current was turned off as soon as immobilization occurred. When the fish regained their equilibrium, they were transferred to a large, non-turbulent holding tank for further observation and were later released into the forebay. No signs of injury were observed among the exposed fish and after resting for several hours they appeared to be as active as fish that had not been exposed to the electrical stimuli.

Tests were also conducted to determine the combinations of frequency and duty cycle of interrupted direct current that would produce the best galvanotropic response. These tests consisted of aligning individual fish parallel to and midway between two parallel wire screen electrodes at the ends of a 67-inch by 93-inch tank and observing whether the fish swam to the anode or the cathode when the voltage was applied. This test tank is shown in Figure 2. Each fish

TABLE 2

EFFECT OF VARIOUS INTERRUPTED DIRECT CURRENT STIMULI ON IMMOBILIZATION OF ADULT SOCKEYE USING A VOLTAGE GRADIENT OF 1.235 VOLTS PER INCH

Sex	Length Inches	Frequency pps.	Duty Cycle Per Cent	Resistivity ohms per inch-cube	Immobilization Time Seconds	Recovery Time Seconds
F	23.2	5	50	4,330	11	201
M	23.6	8	50	4,330	16	23
M	25.0	10	50	4,330	11	30
M	23.0	8	70	4,330	17	24
M	24.0	10	90	4,330	11	15
M	25.2	5	70	2,680	23	12
F	22.8	10	70	2,680	22	20
M	25.6	5	90	2,680	12	60
M	25.2	8	90	2,680	15	13

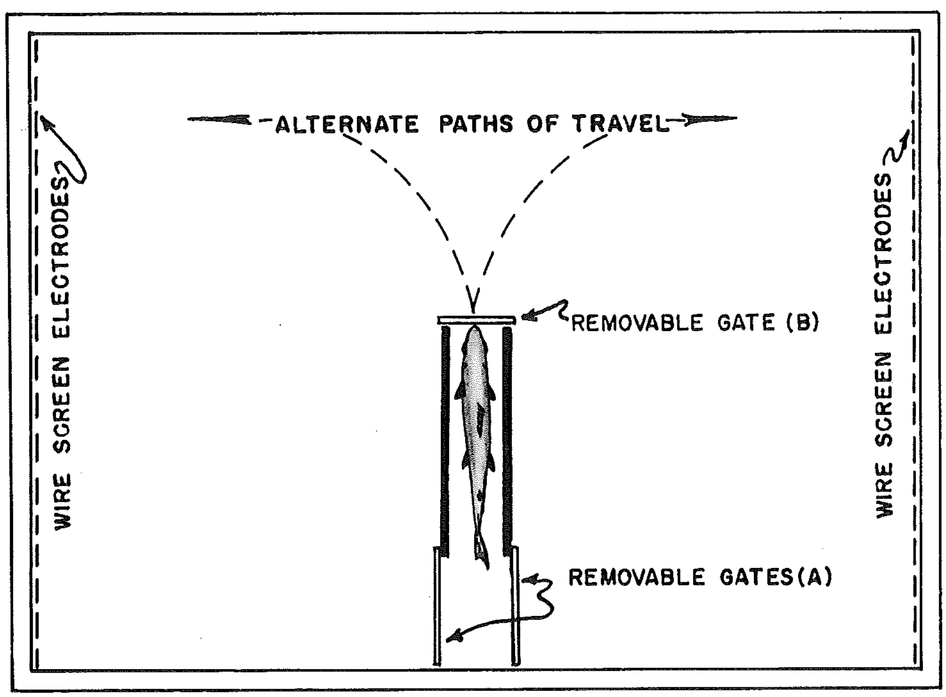

Figure 2. Plan view of experimental tank for testing galvanotropic response of adult sockeye salmon at Baker Dam, 1953.

was guided into the 24-inch by $5\frac{1}{2}$-inch starting trough with its head facing gate B. The gates at A were then closed and the power was turned on. When gate B was opened, the fish ventured into the electrified area and swam either to the anode or to the cathode. The power was turned off as soon as the fish reached an electrode. Five trials were made with each fish. The polarity was reversed after each trial so that the position of the anode was alternated between the two ends of the tank for successive trials. The water was changed frequently, the depth maintained at 12 inches. Water resistivity ranged from 2,850 to 3,220 ohms per inch-cube and temperature ranged from 52 to 56°F.

Table 3 is a compilation showing the relative galvanotropic response to direct current and various combinations of frequency and duty cycle of interrupted direct current at a voltage gradient of 0.38 volts per inch. The results indicated that adult sockeye exhibit a galvanotropic reaction when exposed to either direct current or interrupted direct current. At the given voltage gradient, the galvanotropic response tended to increase as the frequency and duty cycle were increased. This finding was somewhat similar to that obtained in experiments with yearling sockeye where it was shown that a higher voltage gradient was required to elicit, with a low duty cycle, the same response as obtained with a higher duty cycle. At a voltage gradient of 0.38 volts per inch, and in water with a resistivity of 3,000 ohms per inch-cube, the best galvanotropic response seemed to occur when the frequency was about 8 pulses per second and the duty cycle was about 80 per cent. When the frequency was low, fish tended to turn away from the anode during the "off time" between pulses. When the frequency was high, the swimming ability of the fish was impaired and they appeared to become fatigued more rapidly. Fish exhibited distress when swimming towards the cathode but swam towards the anode with much

TABLE 3

RELATIVE ATTRACTION OF ADULT SOCKEYE TO ANODE USING DIRECT CURRENT AND INTERRUPTED DIRECT CURRENT AS THE STIMULUS

Voltage Gradient 0.38 volts per inch, resistivity 2,850 to 3,220 ohms per inch-cube.

Frequency	Duty Cycle in Per Cent								
pps.	1	10	30	50	70	80	90	99	DC
1		40/5		40/5	60/5		100/5		
3	60/5	50/10	60/10	73/15	80/25		70/10	40/5	
5	60/5	60/15	73/15	85/20	70/20	60/5	80/15	60/5	
7	60/10	80/20	93/15	72/25	80/30		70/20	100/10	
8	60/5	100/10	90/10	70/10	100/20	100/5	100/10	60/5	
9	40/5	100/10	90/20	100/10	75/20		80/10	100/5	
10	80/10	100/10	60/10	80/30	93/15	100/5	90/10	80/5	
DC									90/10

Note: 60/5 indicates that in five trials, the fish turned to the anode 60 per cent of the time.
85/20 indicates that four different fish were used, each with five trials, and that in 20 trials these fish turned to the anode an average of 85 per cent of the time.

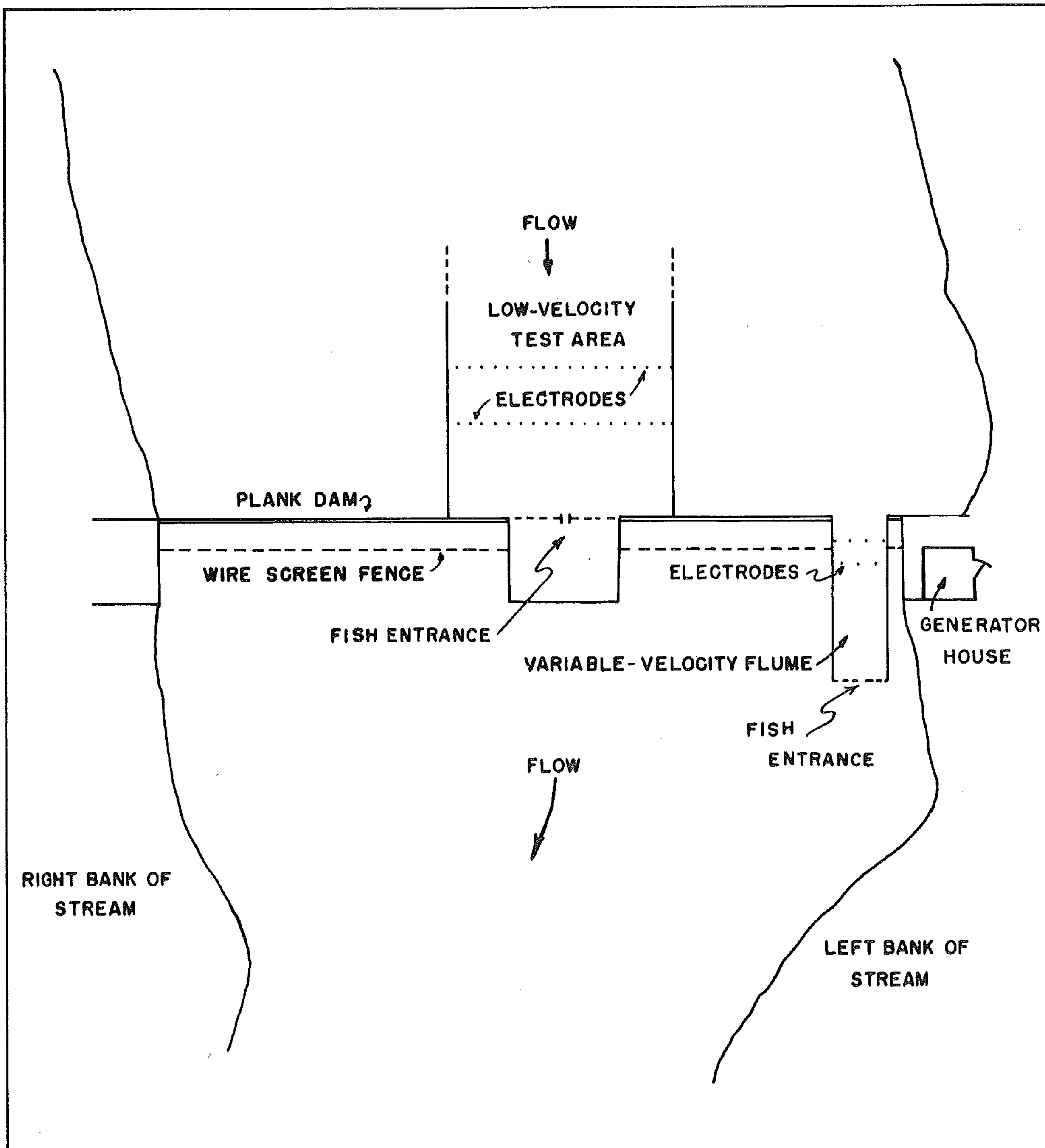

Figure 3. Plan view of installations for electrical experiments with adult salmon in Sweltzer Creek, 1953.

less difficulty.

FIELD STUDIES OF EFFICIENCY OF ELECTRIC SCREENS

Following the preliminary findings at Baker Dam, a program of experiments was conducted in Sweltzer Creek near the outlet of Cultus Lake from September 24 to November 4, 1953 to investigate the efficiency of electrical methods for guiding adult sockeye and pink salmon under natural conditions in a stream. The objectives of this investigation were: first, to determine the effectiveness of an electric screen placed perpendicular to the direction of stream flow; second, to determine whether adult salmon could be directed upstream along a galvanotropic screen placed at an angle to the direction of stream flow; third, to determine the relative effectiveness of various types of electrical stimuli; and fourth, to determine the effect of different water velocities on the efficiency of an electric screen.

The experimental facilities for these studies were installed in Sweltzer Creek about 1,000 feet downstream from Cultus Lake (Figure 3). A wire screen fence was constructed across Sweltzer Creek to lead the fish into two experimental areas, a low-velocity test area 32 feet wide by 40 feet long and a variable-velocity flume 8 feet wide by 24 feet long. A plank dam 2 feet high maintained a water depth of 2.5 to 3.0 feet in the test area and 1.5 to 2.0 feet in the flume.

The sides of the low-velocity test area were built of plywood; the upstream end was left open and the downstream end was screened with vertical 1-inch diameter wooden rods spaced 2 inches from center to center. Fish entered the test area through a 6-inch wide vertical slot in the center of the picketed downstream end. The bottom of the test area consisted of gravel ranging up to 3 inches in diameter and was levelled to provide nearly uniform depths over the entire area. The electrodes, 1-inch diameter galvanized iron rods, were supported vertically and extended from the gravel bottom to the water surface. Walkways were built around this test area to permit good observation.

The variable-velocity flume, built adjacent to the left bank of the stream, was 8 feet wide, 24 feet long and 3 feet deep with a level bottom. It was covered with tarpaulins to eliminate direct sunlight. The walls and bottom were built of 2-inch planks and the upstream end was open except for vertical 1-inch by 6-inch baffles 3 feet long spaced 8 inches apart and extending from the water surface to the bottom. The downstream end was screened with vertical 1-inch diameter wooden rods spaced 2 inches from center to center. Fish entered the flume through a 6-inch wide slot in the center of the downstream end. A wire screen fence placed a short distance upstream from the baffles prevented fish from re-entering the flume from the upstream end. The water velocity through the flume was controlled by adjusting the discharge at the downstream end.

Power generating equipment was housed in an 8-foot square shed on the left bank of the stream. Direct current was obtained from a 1.5-kilowatt 120-volt shunt-wound direct current generator. To obtain interrupted direct current, the output of the generator was fed through a rotating switch. To obtain variable-voltage 60-cycle alternating current, a 1-kilowatt isolating transformer and a variable-voltage transformer were used. Half- or full-wave rectified 60-cycle alternating current was obtained using thyratron tubes on the output side of the isolating transformer. The voltage applied to the electrodes was measured with an oscillograph. In all cases, the voltages stated in the results are peak-to-peak values. That is, the intensity of the stimulus has been expressed in terms of the change in potential from the maximum positive voltage to zero or, for alternating current, from the maximum positive voltage to the maximum negative voltage. The peak-to-peak voltage is divided by the distance in inches between the electrode rows to give a nominal voltage gradient in volts per inch.

There was considerable variation in the lengths of the 13,169 fish used in the experiments. Most of the fish were 4-year-old sockeye having an average fork length of 24.7 inches for males and 22.8 inches for females but some 3-year-old jack sockeye having an average length of 18.8 inches were also used in the experiments. The male pink salmon had an average length of 23.6 inches and the females averaged 21.7 inches. Table 4 shows the numbers and lengths of fish in each group. At the beginning of the experiment the fish consisted mainly of sockeye but towards the end of the experiment the migrating population consisted predominantly of pink salmon.

The water in Sweltzer Creek was usually very clear during the tests but occasionally surface runoff from a heavy rain caused the water to become turbid. On these occasions the electrical experiments were discontinued because it was impossible to make accurate observations of the activity of the fish. Twenty-five measurements of specific resistance showed that during the main part of the experiments the resistivity of the water varied from 3,500 to 4,000 ohms per inch-cube. The highest reading obtained during the experiment was 4,530 and the lowest was 2,990. These readings were made with an Industrial Instruments Model RC1 conductivity bridge with a neoprene dip cell (cell constant = 1).

Five persons were required for conducting the tests in each test area. One man adjusted the electrical equipment and remained at the controls. When the

TABLE 4

NUMBERS AND LENGTHS OF SALMON USED IN THE ELECTRICAL EXPERIMENTS AT CULTUS LAKE IN 1953

Species	Number in Tests	Number Measured	Max. Length Inches	Min. Length Inches	Average Length Inches
Sockeye					
Adult Females	3,181	255	25.4	21.5	22.8
Adult Males	5,003	149	28.2	21.5	24.7
Jacks	874	266	21.2	15.9	18.8
Pinks					
Females)	4,111	99	24.2	19.7	21.7
Males)		105	27.0	20.1	23.6

power was turned on, the gate at the downstream end of the test area was opened and one observer, with the aid of a number of hand tallies, recorded the species, sex, and an estimate of the lengths of fish entering the test area. Another man counted the number of attempts ("trials") made to get through the electrified area by each species and also the number of fish that escaped. A fourth observer checked the sex and species of escaping fish and, when possible, estimated their lengths. The fifth man observed and recorded the activity of the fish and the effect of the electrical stimuli on swimming ability and immobilization. A total of 182 tests including controls were conducted, each lasting about 30 minutes.

TESTS IN THE LOW-VELOCITY TEST AREA

The purpose of the tests conducted in the low-velocity test area was to determine what combinations of electrical conditions and electrode arrangements would be most effective in controlling the upstream migration of adult salmon in low water velocities. These tests were divided into three series. In the first and second series, galvanotropic screens were placed directly across the width of the test area to determine their effectiveness in stopping the upstream migration. The first series was conducted to measure the effects of duty cycle, pulse frequency, and voltage gradient of the applied stimulus; the second, to determine the effect of electrode arrangement. The third series was conducted to determine whether adult salmon could be guided upstream along an electric screen into a by-pass if the screen were placed at an angle to the stream flow. The water velocity remained almost uniform in the test area during the experimental period, the average velocity being 0.73 feet per second.

Effect of Duty Cycle, Pulse Frequency and Voltage Gradient

In the first series of tests, vertical 1-inch diameter electrodes were arranged in two parallel rows, perpendicular to the stream flow, with the anode downstream. The electrode rows were spaced 12 feet apart with the electrodes in the cathode row spaced 2 feet apart and those in the anode row spaced at 1 foot and 3 feet alternately. With this arrangement, different combinations of voltage gradient, duty cycle and pulse frequency of interrupted direct current were applied. The results of these tests are shown in Table 5.

The duty cycle greatly influenced the effectiveness of the screen. At a given voltage gradient and frequency, duty cycles of long duration were more effective than those of short duration. At a voltage gradient of 0.75 volts per inch and a frequency of 8 pulses per second, the increase in screen effectiveness in stopping the fish is shown by the following comparison:

Duty cycle (per cent)	10	30	50	70	80	90	95
Effectiveness (per cent)	15	50	80	90	85	80	75

Duty cycles of 70 and 80 per cent appeared to produce the best galvanotropic responses.

The pulse frequency had less effect than the duty cycle. When the frequency was varied over a range of 1 to 12 pulses per second, differences in the effectiveness of the electric screen were not pronounced but slight increases in effectiveness were indicated at the higher frequencies. Highest efficiencies were obtained within the range of 5 to 12 pulses per second and the optimum frequency appeared to be 8 or 10 pulses per second.

The voltage gradient appeared to be the most important factor. At a voltage gradient of 0.5 volts per inch the screen was less than 30 per cent

TABLE 5

EFFICIENCY OF GALVANOTROPIC SCREENS FOR STOPPING THE UPSTREAM MIGRATION OF ADULT SALMON

Stimulus: Interrupted direct current.

Electrodes: 1-inch diameter vertical rods in two rows 12 feet apart with a spacing of 2 feet in the upstream row and 1 foot and 3 feet alternately in the downstream row.

Date	Voltage Gradient v/in.	Duty Cycle %	Frequency pps.	No. of Sockeye	No. of Pinks	% Held Back	Immobilization
October							
2	0.83	2	5	8		12.5	
1	0.83	2	10	10		0	Slight
7	0.75	10	8	102	1	11.3	None
8	0.75	10	8	219	9	18.9	None
7	0.75	10	12	43	1	4.3	None
8	0.75	30	8	110	10	48.5	None
6	0.75	50	1	93		50.5	
6	0.75	50	3	79		67.0	None
6	0.75	50	5	83		77.4	
6	0.75	50	8	39		84.5	None
8	0.75	50	8	158	5	77.8	Slight
6	0.75	50	8	106		79.2	
6	0.75	50	12	73		73.7	Severe
8	0.75	70	8	126	2	92.1	Slight
8	0.75	80	8	62	3	89.4	Slight
9	0.75	80	8	67	2	84.0	Slight
8	1.00	80	8	56	3	88.4	Severe
3	0.75	90	3	50		78.8	
4	1.00	90	3	63		92.1	Considerable
4	0.85	90	7	75		84.5	Considerable
4	1.00	90	7	70		91.6	Severe
3	0.75	90	7.5	72		71.7	Considerable
5	0.25	90	8	48		15.4	None
5	0.50	90	8	68		25.0	None
5	0.75	90	8	76		83.3	
8	0.75	90	8	131	8	75.0	Slight
5	1.00	90	8	80		95.0	Considerable
4	0.75	90	9	97		78.6	Considerable
3	0.75	90	10	99		85.4	Considerable
5	1.00	90	10	25		96.0	Severe
4	0.75	90	12	114		86.0	Considerable
7	0.75	95	1	69		71.9	Slight
7	0.75	95	3	84	1	77.6	Slight
6	0.75	95	5	71		68.5	
7	0.75	95	5	123	5	83.1	
7	0.75	95	8	88	2	74.5	Slight
6	0.75	95	12	50		70.0	Considerable

effective in stopping fish but when the voltage gradient was raised to 0.75 volts per inch its effectiveness was increased to 80 per cent. With a voltage gradient of 1.0 volt per inch, efficiencies up to 96 per cent were obtained. It is important to note, however, that an increase in voltage gradient caused an increase in immobilization. Obviously all of the fish could be held back by an electrical barrier with any type of electrical stimulus provided the voltage gradient was high enough to critically impair the swimming ability of the fish or immobilize them so they would be unable to swim through the electrified area. In low water velocities, however, immobilized fish tend to settle to the bottom and are subjected to prolonged exposure. The classification "considerable" immobilization shown in Table 5 indicates that practically all of the fish that entered the electrified area were temporarily immobilized but their swimming ability was not impaired to the extent that they settled to the bottom in the electrified area. "Severe" immobilization indicates that fish were severely stunned by electrical exposure and that in some cases fish were killed after settling to the bottom and remaining in the electrified area. Even when many fish were severely immobilized some were able to penetrate the screen and escape upstream. It is indicated, therefore, that electric screens operating in low water velocities would not be completely effective because some fish would be killed and some would escape through the electrified zone.

Effect of Electrode Arrangement

The second series of experiments in the low-velocity test area was conducted to determine the effect of electrode arrangement on the efficiency of the electric screen. These experiments were conducted using what appeared to be the most efficient galvanotropic stimulus - interrupted direct current at a duty cycle of 80 per cent and a frequency of 8 pulses per second. Results of this study are shown in Tables 6 to 8. The downstream row was the anode in all of

TABLE 6

EFFICIENCY OF GALVANOTROPIC SCREENS FOR STOPPING
THE UPSTREAM MIGRATION OF ADULT SALMON

Stimulus: Interrupted direct current, 8 pulses per second, 80 per cent duty cycle.

Electrodes: 1-inch diameter vertical rods in two rows 12 feet apart.

Date	Voltage Gradient v/in.	Spacing in Upstream Row ft.	Spacing in Downstream Row ft.	No. of Sockeye	No. of Pinks	% Held Back	Immobilization
Electrodes in downstream row placed in line with those in upstream row.							
Oct.							
9	0.75	2	2	73	1	82.9	
9	0.75	2	4	104	1	76.6	Slight
9	0.75	3	3	108	3	78.6	Slight
10	0.75	3	3	89	5	85.4	Slight
10	1.00	3	3	56	1	89.6	Severe
10	0.75	3	6	65	3	73.6	Considerable
9	0.75	4	4	74	2	70.5	
9	0.75	4	8	104	3	65.2	
10	0.75	6	3	74	6	65.9	Slight
10	0.75	6	6	72	1	62.4	Slight
9	0.75	8	8	99	5	25.2	Slight
Electrodes in downstream row staggered with respect to those in upstream row.							
9	0.75	4	4	94		74.0	Slight
10	0.75	6	6	71	5	58.7	Slight
9	0.75	8	8	83	1	12.4	
9	1.00	8	8	28	1	32.2	Slight

TABLE 7

EFFICIENCY OF GALVANOTROPIC SCREENS FOR STOPPING
THE UPSTREAM MIGRATION OF ADULT SALMON

Stimulus: Interrupted direct current, 8 pulses per second, 80 per cent duty cycle.

Electrodes: 1-inch diameter vertical rods in two rows 8 feet apart.

Date	Voltage Gradient v/in.	Spacing in Upstream Row ft.	Spacing in Downstream Row ft.	No. of Sockeye	No. of Pinks	% Held Back	Immobilization
Electrodes in downstream row placed in line with those in upstream row.							
Oct.							
11	0.75	2	2	71		94.5	
11	1.00	2	2	82		96.5	
12	1.00	2	8	78	5	86.2	
12	1.00	4	4	73	6	79.8	
12	1.00	4	8	102		73.0	Slight
12	1.00	8	2	48		74.0	
Electrodes in downstream row staggered with respect to those in upstream row.							
11	1.00	2	4	68	2	90.1	
12	1.00	2	4	84	9	91.5	Slight
12	1.00	4	4	73	2	89.5	Slight

TABLE 8

EFFICIENCY OF GALVANOTROPIC SCREENS FOR STOPPING
THE UPSTREAM MIGRATION OF ADULT SALMON

Stimulus: Interrupted direct current, 8 pulses per second, 80 per cent duty cycle.

Electrodes: 1-inch diameter vertical rods in two rows 4 feet apart.

Date	Voltage Gradient v/in.	Spacing in Upstream Row ft.	Spacing in Downstream Row ft.	No. of Sockeye	No. of Pinks	% Held Back	Immobilization
Electrodes in downstream row placed in line with those in upstream row.							
Oct.							
13	1.00	2	2	50	3	89.1	
13	1.00	2	4	39	9	74.0	
13	1.00	2	8	51	1	50.0	
13	1.00	4	4	64	2	67.6	
Electrodes in downstream row staggered with respect to those in upstream row.							
13	1.00	2	2	46	2	85.7	
13	1.00	4	4	52	3	84.2	
13	1.50	4	4	51	6	67.2	Considerable
13	2.00	4	4	38	1	95.0	Considerable

these tests. The spacing of electrodes within each row and the spacing between rows was varied to give a number of different combinations.

The spacing of electrodes within rows had a marked effect on the efficiency of the screen. The efficiency decreased as the spacing between adjacent electrodes was increased. With a wide spacing, regions of low field intensity were produced between adjacent electrodes through which fish were able to escape quite easily whereas fish that entered the electrified area close to an electrode were stunned by a concentrated field surrounding the electrode. As the spacing between electrodes was decreased, the electrical field became more uniform and fewer fish were able to escape. Although closely spaced electrodes appeared to be most effective, the spacing of electrodes, especially in the downstream row, had to be great enough to allow fish to move out of the electrified zone without delay. Too small a spacing could hinder the retreat of fish from the electrified zone or cause immobilized fish to impinge on the electrodes and be killed by excessive exposure. A 2-foot spacing between adjacent electrodes within rows gave the best results, producing a fairly uniform field and permitting the fish freedom of movement out of the electrified zone.

The spacing between electrode rows was also an important factor. As shown in the tables, the efficiency was higher when the rows were 4 feet apart than when the distance between rows was 12 feet. If the intensity and distribution of current in both of these fields were uniform, fish would experience more difficulty swimming through an electrified area that extended over a distance of 12 feet than through one that was only 4 feet wide. However, with the greater distance between the rows there was some spreading of the lines of current flow through the gravel bottom of the test area. Consequently, the field intensity with the 12-foot spacing was concentrated near the electrodes and became relatively weak towards the center of the electrified zone. Therefore, fish that swam past the downstream row of electrodes encountered less intense stimulation as they moved farther into the electrified zone until they reached a point midway between the two electrode rows. Being able to maintain their swimming ability and speed in the relatively weak field near the center of this zone, they were able to escape quite easily. With the 4-foot spacing between electrode rows the field intensity was more uniformly distributed throughout the electrified area. It seems likely, however, that the optimum spacing between electrode rows would depend on the depth and velocity and the resistivity of the bottom materials at the location to be screened. In these experiments, the highest guiding efficiencies were obtained with an 8-foot spacing between rows.

The relation between the position of electrodes in one row with respect to those in the other also affected the efficiency of the screen. When electrodes in the upstream row were directly in line with those in the downstream row, the efficiency of the electric screen was lower than when the electrodes of the two rows were staggered with respect to each other. The increase in efficiency with the staggered arrangement was pronounced when the distance between the two electrode rows was 4 feet but became less apparent as the distance between rows was increased.

Thus, these tests in low water velocities indicated that the most effective arrangement for 1-inch diameter vertical electrodes consisted of a spacing of 2 feet between electrodes in each row, with the two rows spaced 8 feet apart, and with the position of the electrodes in one row staggered with respect to the position of those in the other row. It will be shown, however, that an arrangement consisting of a greater spacing between electrodes in each row and a lesser spacing between the two rows was satisfactory when the water velocity was high enough to carry immobilized fish out of the electrified area.

Effect of Screen Position

The third series of tests was conducted in the low-velocity test area to determine whether an electric screen placed at an angle to the stream flow would be effective in guiding fish to a by-pass. For these experiments, vertical 1-inch diameter galvanized iron electrodes were arranged in two parallel rows at an angle of 45 degrees to the stream flow, with a distance of 4 feet between rows and a spacing of 3 feet between electrodes within the rows. This arrangement is shown in Figure 4. In the first group of tests, an unobstructed gap 5 feet wide was left between the upstream end of the screen and the left wall to serve as a by-pass. For other tests the electrode rows were extended to the left wall, closing the gap, and a 2-foot wide slot (by-pass) was cut through this wall 20 feet farther downstream. Finally, the width of the by-pass opening was increased to 8 feet. Interrupted direct current was used in all these tests. The results of the tests are shown in Table 9.

Although the electrodes were at an angle to the stream flow the fish did not follow along the screen to the by-pass. When fish entered the electrified area they became extremely active and usually darted back downstream immediately. Some moved laterally across the test area for short distances before retreating from the electrified zone but this lateral movement was as often away from the by-pass as towards it. Some fish escaped through the electrified area and a few were immobilized and settled to the bottom in the electrified area. When the 5-foot gap was left open at the upstream end of the screen to serve as a by-pass, large numbers of fish accumulated in the area downstream from the electrodes and very few fish moved upstream through the opening. The 2-foot wide by-pass in the left wall was also ineffective even though there was a velocity of 1.25 feet

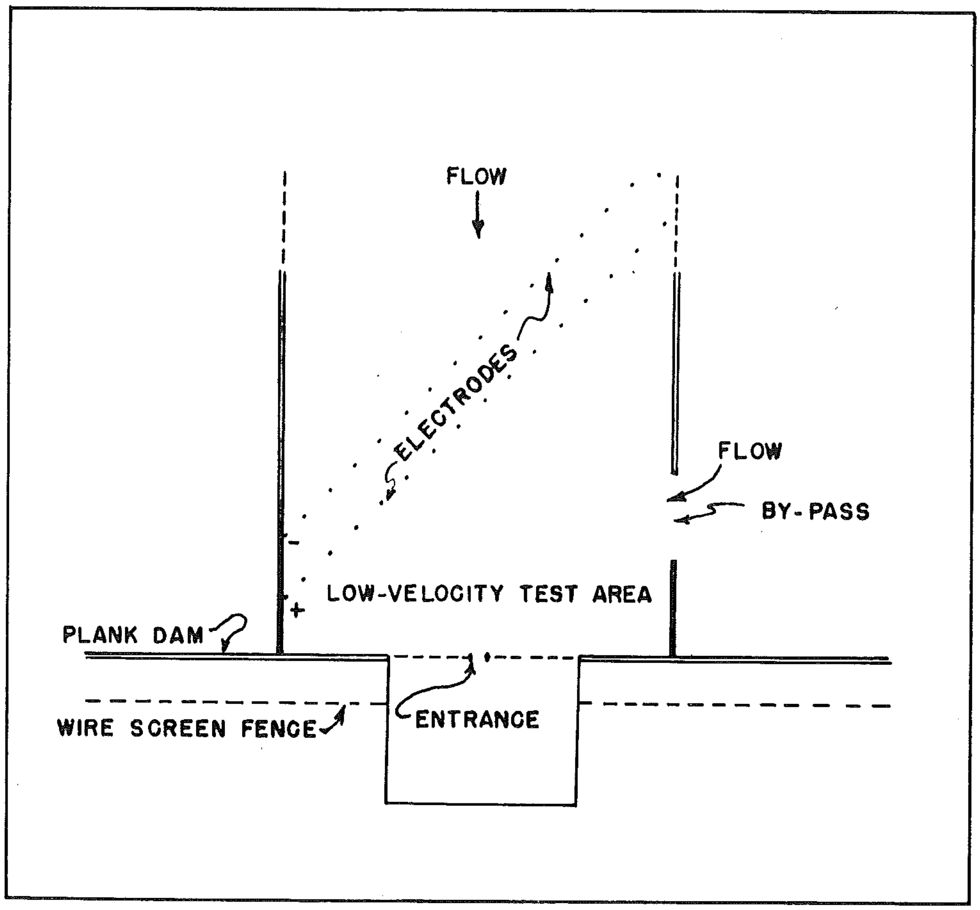

Figure 4. Plan view of the low-velocity test area showing the galvanotropic screen and the by-pass.

TABLE 9

PERCENTAGE OF ADULT SOCKEYE AND PINK SALMON DIVERTED BY AN ELECTRIC SCREEN PLACED AT AN ANGLE OF 45° TO THE STREAM FLOW, WITH A BY-PASS LOCATED IN ONE WALL OF THE TEST AREA

Electrodes: 1-inch diameter, in two rows 4 feet apart, with a spacing of 3 feet between electrodes in each row.

Stimulus: Interrupted direct current.

Voltage	Frequency pps	Duty Cycle %	No. of Sockeye	No. of Pinks	% Held Back or By-passed	% By-passed	By-pass No.
Control			98	13	19.6	0	2
Control			41	9	18.2	16.2	3
Control			78	25	5.8	0	3
Control			67	10	12.2	10.1	3
96	8	80	68	4	95.2	12.2	1
96	8	80	92	5	92.6	32.4	2
96*	8	80	94	19	97.5	6.8	2
96	8	80	56	34	95.7	81.6	3
96	8	80	36	16	96.2	75.5	3
96	8	80	98	6	95.2	51.4	3
96	8	80	56	32	89.1	71.8	3
72	8	80	75	20	74.3	64.7	3
120*	8	80	85	33	99.2	63.6	3
120	8	10	73	23	85.9	80.9	3
150	8	10	97	23	67.5	79.3	3
150*	8	30	56	13	78.2	71.8	3
150*	8	50	59	11	80.7	69.9	3
140*	8	80	49	27	95.0	86.3	3
120	8	90	74	23	86.0	73.8	3

* Some fish killed or severely stunned in these tests.

By-pass Description:

No. 1 - Gap in electric screen 63 inches wide between upstream end of electrode array and left wall of test area.

No. 2 - Hole cut in left wall of test area, 24 inches wide by 30 inches deep, center of opening 15 feet upstream from lower end of test area.

No. 3 - Hole cut in left wall of test area, 96 inches wide by 36 inches deep, center of opening 12 feet upstream from lower end of test area.

per second flowing into the test area through this opening. When the width of the by-pass opening was increased to 8 feet, so that a relatively large flow of water was discharged into the test area at right angles to the main direction of flow, the number of fish accumulating in the area downstream from the electrodes was reduced. In 12 tests, approximately 72 per cent of the fish entering the test area swam out through the 8-foot wide by-pass opening when the electric screen was operating whereas approximately 9 per cent used this by-pass during the controls. However, there was considerable delay in finding and using the by-pass exit. The electric screen did not guide the fish to the by-pass, it merely served to accumulate some fish in the test area and this resulted in an increased number of fish finding and using the by-pass.

The results of these tests in low water velocities (0.73 feet per second) showed that a galvanotropic screen placed at an angle of 45 degrees to the stream flow was as effective for stopping the upstream migration as one placed at 90 degrees to the stream flow but was not effective in leading the fish to a by-pass. Both these screens stopped nearly all of the fish either by attracting them back downstream, impairing their swimming ability, or by immobilizing them in the electrified area. However, two important results should be emphasized; first, although some fish escaped through the electric screen, other fish were severely immobilized when they settled to the bottom in the electrified zone; and second, fish made repeated attempts to swim through the electrified zone and did not follow along the electric screen to the by-pass.

TESTS IN THE VARIABLE-VELOCITY FLUME

The purpose of the tests conducted in the variable-velocity flume was to determine the effect of water velocity on the efficiency of an electric screen and to measure the relative effect of various electrical stimuli. Average water velocities in the flume were varied from 0.5 fps to 3.0 fps and five different electrical stimuli were tested; direct current, interrupted direct current, 60-cycle alternating current, full-wave rectified and half-wave rectified 60-cycle alternating current.

The same electrode arrangement was used for all tests. The screen consisted of two parallel rows of 1-inch diameter galvanized iron rod electrodes extending vertically from the bottom of the flume to the water surface. The rows were 4 feet apart and perpendicular to the stream flow. Electrodes were spaced 2.5 feet apart within the rows and the electrodes in one row were staggered with respect to those in the other. The upstream row of electrodes was located 3 feet from the upstream end of the flume and comprised 3 vertical electrodes. Four electrodes were used in the downstream row, which was the anode except when alternating current was used. The results of these tests are shown in Tables 10 to 13.

Effect of Water Velocity

It was evident that the water velocity greatly influenced the efficiency of the electric screen. All fish were stopped when the water velocity exceeded the swimming speed of fish impaired by the electric current. When water velocities were low, many fish were able to swim through the screen even though their swimming ability was impaired. The water velocity required to stop impaired fish was related to the applied voltage. In general, a velocity of 3 feet per second was required when the voltage gradient was 1.5 volts per inch, 2.5 feet per second at 2.0 volts per inch and 2.0 feet per second at 2.25 volts per inch.

TABLE 10

EXPERIMENTS WITH ELECTRIC SCREENS FOR STOPPING ADULT SOCKEYE AND PINK SALMON IN 8-FOOT WIDE FLUME

Electrodes: 1-inch diameter, 30 inches apart, anode row 48 inches downstream from cathode row.

Stimulus: Interrupted direct current, 8 pulses per second, 80 per cent duty cycle.

Date	Duration Mins.	Voltage v/in.	Velocity fps	SOCKEYE Total Fish	SOCKEYE Average Trials Per Fish*	SOCKEYE Per Cent Held Back	PINKS Total Fish	PINKS Average Trials Per Fish*	PINKS Per Cent Held Back
1953									
Oct. 20	23	1.50	2.37	17	1.71	94.1	20	1.10	95.0
29	14	1.50	2.38	9	2.67	66.7	120	1.56	93.5
19	30	1.50	2.80	42	1.55	97.6	23	1.82	100.0
30	20	1.50		9	3.89	100.0	144	1.86	97.2
28	30	1.58	0.60	3	1.33	66.6	63	1.71	73.0
28	11	1.58	2.30	9	1.22	100.0	76	1.09	98.7
28	30	2.00	0.60	16	2.44	87.3	58	1.88	96.5
Nov. 4	37	2.00	1.52	2	4.00	50.0	28	3.00	100.0
3	20	2.00	1.87	3	2.33	100.0	47	2.32	100.0
Oct. 20	30	2.00	2.11	27	1.78	100.0	40	2.22	100.0
28	17	2.00	2.30	8	3.25	100.0	89	1.37	100.0
29	20	2.00	2.32	2	1.50	100.0	57	2.07	99.2
20	27	2.00	2.37	17	1.70	94.0	20	1.10	95.0
29	20	2.00	2.38	6	4.67	100.0	117	1.65	100.0
30	20	2.00		7	1.14	100.0	179	1.80	100.0
28	13	2.50	0.60	29	2.07	91.8	31	2.42	96.0
Nov. 3	20	2.50	1.87	6	3.17	100.0	40	2.73	97.5
Oct. 21	35	2.50	2.99	23	3.58	100.0	31	1.64	100.0

$$\text{* Average Trials Per Fish} = \frac{\text{Number of times fish entered the electrified zone}}{\text{Number of fish in the test}}$$

TABLE 11

EXPERIMENTS WITH ELECTRIC SCREENS FOR STOPPING ADULT SOCKEYE AND PINK SALMON IN 8-FOOT WIDE FLUME

Electrodes: 1-inch diameter, 30 inches apart, anode row 48 inches downstream from cathode row.

Stimulus: Direct current.

Date	Duration Mins.	Voltage v/in.	Velocity fps	SOCKEYE Total Fish	SOCKEYE Average Trials Per Fish	SOCKEYE Per Cent Held Back	PINKS Total Fish	PINKS Average Trials Per Fish	PINKS Per Cent Held Back
1953									
Oct. 29	20	2.00	2.32	12	2.00	91.6	107	1.33	94.3
21	25	2.00	2.99	54	13.9	100.0	21	2.38	95.2
30	20	2.00		11	3.00	100.0	123	1.87	93.5
27	27	2.00		9	3.00	77.7	47	1.59	42.5
29	20	2.50	2.32	5	0.60	100.0	88	1.52	100.0
21	26	2.50	2.99	58	1.79	100.0	33	1.52	100.0
30	20	2.50		5	5.20	100.0	95	2.17	100.0

TABLE 12

EXPERIMENTS WITH ELECTRIC SCREENS FOR STOPPING ADULT SOCKEYE AND PINK SALMON IN 8-FOOT WIDE FLUME

Electrodes: 1-inch diameter, 30 inches apart in two rows 48 inches apart.

Stimulus: 60-cycle alternating current.

				SOCKEYE			PINKS		
Date	Duration Mins.	Voltage v/in.	Velocity fps	Total Fish	Average Trials Per Fish	Per Cent Held Back	Total Fish	Average Trials Per Fish	Per Cent Held Back
1953									
Oct. 19	20	1.00	2.80	47	1.38	29.8	16	1.00	31.3
29	20	1.50	2.32	6	0.67	66.6	71	1.52	89.0
19	36	1.50	2.80	31	1.48	67.7	19	1.47	47.0
29	20	2.00	2.32	11	1.55	100.0	100	1.43	100.0
20	28	2.00	2.37	40	1.27	95.0	60	2.00	95.0
19	41	2.00	2.80	50	1.14	100.0	12	2.50	91.6
23	55	2.50	1.79	10	1.70	100.0	48	2.12	100.0
20		2.50	2.37	18	1.78	100.0	43	1.95	100.0
23	17	2.50	2.51	19	1.47	100.0	49	1.42	100.0

TABLE 13

EXPERIMENTS WITH ELECTRIC SCREENS FOR STOPPING ADULT SOCKEYE AND PINK SALMON IN 8-FOOT WIDE FLUME

Electrodes: 1-inch diameter, 30 inches apart, anode row 48 inches downstream from cathode row.

Stimulus: Rectified 60-cycle alternating current.

				SOCKEYE			PINKS		
Date	Duration Mins.	Voltage v/in.	Velocity fps	Total Fish	Average Trials Per Fish	Per Cent Held Back	Total Fish	Average Trials Per Fish	Per Cent Held Back
1953									
	Full-wave rectified								
Oct. 19	15	1.00	2.80	74	1.24	85.2	6	2.00	33.0
29	20	1.50	2.38	3	1.60	100.0	115	1.55	97.5
19	15	1.50	2.80	42	1.88	97.7	16	1.31	100.0
22	30	2.00	2.16	21	2.48	90.5	13	1.77	100.0
29	20	2.00	2.38	3	4.00	100.0	95	1.56	100.0
22	38	2.50	2.16	23	1.26	100.0	24	1.17	100.0
	Half-wave rectified								
29	20	1.00	2.38	8	2.25	87.5	107	1.82	91.5
19	42	1.00	2.80	53	1.08	73.6	7	1.72	43.0
20	30	1.50	2.37	37	2.11	91.9	29	2.00	100.0
29	20	1.50	2.38	1	6.00	100.0	120	1.42	100.0
19	77	1.50	2.80	56	1.75	89.3	22	1.32	95.5
22	42	2.50	2.16	12	1.83	100.0	26	1.65	96.1
22	45	2.79	2.16	15	1.33	100.0	47	1.57	100.0

That is, lower water velocities were permissible when the intensity of the stimulus was increased.

The extent of immobilization was also affected by the water velocity. In low water velocities, immobilized fish tended to settle to the bottom of the flume and remain in the electrified area for a relatively long time. Some were held in back eddies behind the electrodes and severely stunned or killed. Severe immobilization and death were prevented, however, when water velocities in the flume were high enough to carry immobilized fish out of the electrified area without delay. After being exposed to the electric screen, the fish appeared to be fatigued and some were carried downstream a distance of 17 feet and became impinged on the picketed barrier at the downstream end of the flume. The electric screen was 100 per cent effective for stopping fish without causing severe immobilization when water velocities in the flume exceeded 2.0 feet per second.

Effect of Type of Stimulus

The effectiveness of the electric screen varied only slightly with the different stimuli tested. The screen was just as effective with 60-cycle alternating current, having a change in potential from 48 volts positive to 48 volts negative, as it was with the other stimuli, which had a peak positive potential of 96 volts or greater, and yet the peak current required for 60-cycle alternating current was half or less than half that required for the others. From the standpoint of power consumption, 60-cycle alternating current was more efficient than the other electrical stimuli tested.

Table 14 shows the calculated minimum power consumption for each of the different stimuli at intensities high enough to stop all of the fish in water velocities of approximately 2.5 feet per second. The specific resistance of the water was 4,000 ohms per inch-cube. These calculations assume a uniform voltage gradient in the electrified area but since this is impossible to attain

TABLE 14

MINIMUM VOLTAGES AND CALCULATED POWER CONSUMPTIONS REQUIRED FOR STOPPING ADULT SOCKEYE AND PINK SALMON IN A WATER VELOCITY OF 2.5 FEET PER SECOND WITH A WATER RESISTIVITY OF 4,000 OHMS PER INCH-CUBE

Stimulus	Total Volts Change in Potential	Expressed as Root Mean Square Voltage	Calculated Power Consumption in Watts Per Square Foot of Screened Area*
Alternating current	96	33.9	0.86
Half-wave rectified alternating current	134	67.0	3.37
Full-wave rectified alternating current	96	67.9	3.46
Interrupted direct current (80 per cent duty cycle)	96	85.9	5.53
Direct current	120	120.0	10.80

* Calculated power $= \frac{V^2}{R}$ where V = RMS voltage
R = Resistance of a column of water 4 ft. long, 1 ft. square.
$= \frac{\rho L}{A} = \frac{4{,}000\ (48)}{144} = 1{,}333$ ohms.

with cylindrical electrodes, the calculated power consumptions given in the table are slightly high. The error, however, is proportional regardless of the type of electrical current used. Obviously 60-cycle alternating current was the most economical.

The type of electrical stimulus applied was not important provided the intensity of the stimulus was high enough to impair the swimming ability of the fish and provided the water velocity was high enough to carry immobilized fish out of the electrified area. Because 60-cycle alternating current was more economical than the other stimuli tested, and because it did not appear to have a more adverse effect on the fish than the other stimuli, provided the velocity criterion was met, this stimulus appears to be more advantageous than the others. Holmes (1948) shows that 60-cycle alternating current is "near the optimum frequency for efficiency in causing tetanus". He indicates that, because of this fact, "there is danger of breaking bones, tearing muscles, and otherwise injuring tissues" when 60-cycle alternating current is applied to adult salmon. The present study has shown that there is danger of serious physical injury regardless of the type of stimulus used if the fish remain in the electrified area for a long period of time but no serious physical injury was observed in these tests even when 60-cycle alternating current was used provided the water velocity exceeded 2.0 feet per second.

SUMMARY

The preliminary studies conducted at Baker Dam showed that adult sockeye salmon exhibit galvanotropism when exposed to direct current or interrupted direct current. In water having a specific resistance of about 3,000 ohms per inch-cube the most efficient galvanotropic stimulus at a voltage gradient of 0.38 volts per inch was interrupted direct current at a frequency of about 8 pulses per second and a duty cycle of about 80 per cent. At a specific

resistance of 3,000 ohms per inch-cube the threshold voltage when the fish faced the cathode was about 0.05 volts per inch but was about double this value when the fish faced the anode. The threshold voltage decreased as the resistivity of the water was decreased. Within the ranges studied, neither frequency nor duty cycle appeared to affect the threshold voltage. At a voltage gradient of 1.235 volts per inch the fish lost their equilibrium in a very short time but recovered quickly if the power was shut off as soon as they lost their equilibrium.

Experiments conducted in the 32-foot wide by 40-foot long low velocity test area in Sweltzer Creek showed that even when efficient galvanotropic stimuli were used some fish were killed because the water velocity was not high enough to carry them out of the electrified area when their swimming ability became impaired or when they became immobilized. Highest efficiencies were obtained when the two parallel rows of vertical, 1-inch diameter rod electrodes were spaced 8 feet apart and the electrodes within rows were spaced 2 feet apart. Slightly lower efficiencies were obtained with a 4-foot spacing between rows and still lower with a 12-foot spacing. It was reasoned, however, that if the electrical field between the two rows had not been distorted because of current flow through the gravel bottom of the test area, the efficiency would have increased as the distance between the two electrode rows was increased. The efficiency of the screen decreased as the spacing between adjacent electrodes within rows was increased.

The effectiveness of the electric screen increased when the voltage gradient was increased but at the higher voltage gradients some fish were killed. At a given voltage gradient and frequency, duty cycles of long duration were more effective than those of short duration. The most effective galvanotropic stimulus appeared to be interrupted direct current at a frequency of about 8 pulses per second and a duty cycle of about 80 per cent.

When the electric screen was placed at a 45-degree angle to the direction of stream flow the fish made repeated attempts to swim through the electrified area rather than travel upstream along the screen to a by-pass. Although the numbers of fish passing through the by-pass increased when the electric screen was energized, some fish escaped upstream through the electric screen and others were severely immobilized when they settled to the bottom in the electrified zone.

Tests conducted in the 8-foot wide by 24-foot long variable-velocity flume showed that, under certain conditions, adult sockeye and pink salmon could be stopped by an electric screen consisting of two parallel rows of 1-inch diameter vertical electrodes spaced 4 feet apart with the electrodes in each row spaced 2.5 feet apart. The electrical stimulus had to be of sufficient intensity to impair the swimming ability of the fish and the water velocity had to be high enough to carry immobilized fish out of the electrified zone without delay. A minimum velocity of 2 feet per second was considered necessary in order to prevent severe immobilization and to ensure that no fish would escape. When the average water velocity was 2.5 feet per second, the root mean square voltages required were as follows: 60-cycle alternating current, 34; half-wave rectified alternating current, 67; full-wave rectified alternating current, 68; interrupted direct current (80 per cent duty cycle, 8 pulses per second), 86; direct current, 120. Sixty-cycle alternating current was by far the most economical stimulus as far as power consumption was concerned. Voltages lower than those given above were effective when water velocities were higher than 2.5 feet per second.

The information gained from this study did not indicate that electric screens would be effective in guiding adult salmon at dams but that they might be effective in certain applications where it was required only to stop the upstream migration. Provided the water velocity exceeds 2.0 feet per second, adult salmon can be stopped with electric screens but there is no evidence to show that fish follow along an electric screen to a fishway or other by-pass. Furthermore, fish exposed to electrical stimulation become less active and this might affect their ability to reach the spawning grounds or to spawn successfully. Before electric screens can be considered satisfactory for practical use, the biological effects of electrical stimulation must be thoroughly examined.

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