IN SITU EXPERIMENTS WITH COASTAL PELAGIC FISHES TO ESTABLISH DESIGN CRITERIA FOR ELECTRICAL FISH HARVESTING SYSTEMS[1]

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ABSTRACT

In situ experiments to test the efficacy of a scale electrical harvesting system were conducted off Panama City, Fla. with both captured and wild coastal pelagic fishes. Six species of fish were exposed to preselected combinations of pulse rate, pulse width, and voltage by either attracting wild fish or placing captured fish between electrodes. Both captured and wild fish could be effectively controlled with a minimum field strength of 15 V/m, 20 to 35 pulses/s, and a pulse width of more than 0.5 ms. Voltage, pulse width, and pulse rate were equally important for controlling the species tested. Based on these results, resistance measurements were calculated and a potential netless harvesting system specified which would require a minimum energy output of 120 kVA dissipated into an electrode configuration 10 × 5 × 5 m with a load resistance of 0.01558 ohms. The basic design specifications for a prototype pulse generator are provided for netless fish harvesting applications and mid-water trawling.

Commercial fishing for the small, fast-swimming fish schools characterizing much of the pelagic fishery resource in the Gulf of Mexico has been hampered due to a lack in harvesting technology (Bullis and Thompson, 1970). The Southeast Fisheries Center, Pascagoula Laboratory, National Marine Fisheries Service has been engaged in the design and development of an electrical harvesting system capable of economically exploiting this resource. Results from laboratory experiments (Klima, 1972) provided design criteria for a 12-kVA (kilovolt ampere) pulse generator which was used to field test and validate the electrical control parameters and to provide design criteria for a pulse generator capable of commercially harvesting marine fishes from the Gulf of Mexico. This paper describes the results of the electrical in situ experiments using captured and wild fish.

Fishing with electricity was first used in fresh water during the latter part of the 19th century by Ishan Baggs, who was granted a British patent in 1863. Electrical fishing remained in obscurity until after World War I, when McMillan (1928) began to use electricity to systematically guide and lead fish. The use of electrical fishing in the sea has lagged considerably behind that in fresh water because of the high conductivity of salt water, which results in extremely low load resistance and therefore very high current and power requirements for generation of significant field strengths. Kreutzer (1964) showed pulsed direct current could be utilized economically to harvest fish in the sea provided that the field voltage gradient and shape, duration, and rate of impulses are suitable. Electrical stimulation produces either fright, taxis, tetanus, or eventually death, depending upon the electrical field pulse characteristics (Viber, 1967; Halsband, 1967; Lamarque, 1967).

The reaction to various combinations of characteristics varies with species, fish size, and probably other factors (Riedel, 1952; Collins, Volz, and Trefethen, 1954; Bary, 1956; Higman, 1956; Monan and Engstrom, 1963; Kessler, 1965; Halsband, 1967; Klima, 1968); hence, a combination of electrical factors which will induce electrotaxis in one species may induce a fright response or no response in another. As a result, it is critical to know the combination of electrical field characteristics which will produce the desired reaction for each species of interest.

Success of electrical fishing equipment depends upon use of optimum electrical combinations for

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inducing fright, taxis, or even tetanus. These various responses have successfully been used to commercially harvest marine animals. The principal applications include an electrical fish pump for *hardening* menhaden in a purse seine (Kreutzer, 1964), an electrical fish trawl (McRae and French, 1965), and an electrical shrimp trawl (Klima, 1968; Seidel, 1969).

MATERIALS AND METHODS

Test Procedure

Field experiments were performed in the nearshore waters off Panama City, Fla. The test equipment used in evaluating fish response to an electrical field consisted of a deck-mounted pulse generator and an electrode array deployed in the water alongside the vessel. Salinity and temperature ranged from 29.5 to 33.8 ‰ and 28.0° to 29.6°C, respectively.

Two separate groups of experimental animals were used in the experiments and are referred to as captured fish and wild fish, respectively. The first group consisted of 393 Spanish sardines, *Sardinella anchovia* Valenciennes; 397 round scad, *Decapterus punctatus* (Agassiz); 390 scaled sardines, *Harengula pensacolae* Goode and Bean; 228 Atlantic thread herring, *Opisthonema oglinum* (Lesueur); and 37 Atlantic bumper, *Chloroscombrus chrysurus* (Linneaeus). They were attracted by lights at night and caught with a 5-m lift net in the northern Gulf of Mexico and held in a tank of circulated seawater. Prior to testing, each fish was inspected for damage, and only fish in good condition were used. Each fish was exposed to a preselected combination of pulse rates, voltage, and pulse widths by carefully dropping them into the electrical field facing toward and within 1 m of the negative electrode.

The second group (wild fish) was not handled by the investigators but rather was attracted by lights at night to an area between the electrodes positioned next to the boat. When five or more fish were between the electrodes, they were exposed to preselected combinations of pulse rates, pulse widths, and voltage. Visual observations were used to estimate species composition, approximate size, and responses.

To evaluate the in situ effectiveness of the pulse characteristics tested, we measured the percent of fish which escaped from the electrical field and the percent which swam the length of the field to the positive electrode. The captured fish were introduced into the field in such a way that they were forced to turn 180° in order to swim to the anode, whereas the wild fish schools were randomly oriented. Fish not electrically stimulated when placed between the electrodes exhibited immediate escape movement toward the cathode, the side, or down, but usually did not escape by swimming toward the anode since they were dropped into the electrode array facing the cathode. Test fish would occasionally mill between the electrodes for several seconds before slowly moving away and to the side. Wild fish not electrically stimulated would mill between the electrodes. Consequently, the reactions of the electrically stimulated fish were evaluated in terms of electrotaxis or a positive response by their directed behavior to the anode. We considered swimming to the anode a positive response. All other responses were designated negative.

Description of Test Equipment

The pulse generator providing electrical energy to the electrode array had an output capability of 12 kVA at a pulse rate of 50 pulses/s with a peak output voltage of approximately 150 V at a pulse width of 0.8 ms (millisecond). The pulse rate could be varied from 4 to 55 pulses/s, and three different output widths were available with the unit; 0.3, 0.5, and 0.8 ms measured at the 10% power points. Pulse rise time was around 0.05 ms with a sloped decay. The pulse generator output was designed to operate into load resistance of either 0.05 or 0.2 ohm, since the operational array resistance could not be predicted for all variations in field conditions. At these loads, the output pulse was relatively smooth and undistorted, exhibiting only slight imperfections in the decay portion of the waveform. The waveform was distorted with other array resistances (Figure 1).

In Figure 1D, both the output pulse and the recharging compensating pulse are shown.[3] The compensating pulse is an important feature of the pulse generator and is designed to significantly reduce both electrode electrolysis and electrolysis of any incidental metal within the electrical field, such as a ship's hull. Essentially, the same

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[3] Kreutzer, Patent No. 3,363,353; 16 January 1968.

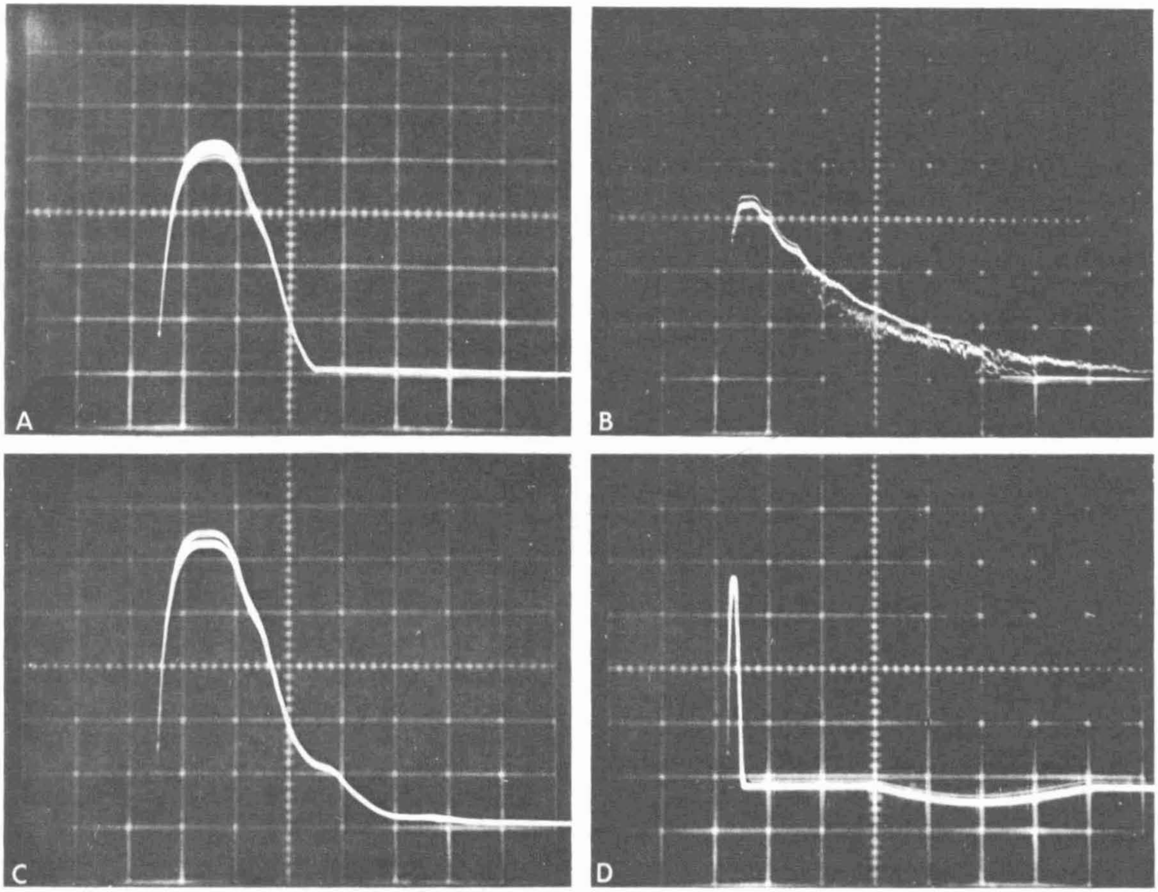

FIGURE 1.—Pulse generator output pulse matched into the load resistance A – low, B – high, C – correctly; the output pulse and compensating pulse are shown in D.

amount of electrical energy is contained within the envelope of the compensating pulse as is within the main pulse except the compensating pulse is of an opposite polarity. The compensating pulse has no effect on fish reaction, since its amplitude is many times less than the main pulse and is below the threshold level of the fish.

The electrode array and pulse generator were designed to effectively energize a minimum volume of water at least 2 m in cross section and 4 m long, and provide a selection of minimum electrical field concentration from 15 to 30 V/m. Each electrode of the array consisted of a copper tube frame with copper strips arranged in a grid pattern. The strips of copper were 15.2 cm wide (6 inches) with square grid openings of 45.7 cm (18 inches) between strips. It has been experimentally demonstrated that the surface of an electrode can be reduced to approximately 10% of the total area and the surface will function electrically as if it were a solid plate (C. Kreutzer,[4] pers. commun.). Our electrode design reduced the conducting surface of the electrode to approximately 53% of the total area. Therefore, this grid technique was utilized to allow the fish to be led to and pass through the anode for easier evaluation of their response. The cable connecting the electrode array to the pulse generator was a 12-m length of 1/0 coaxial conducting cable and represented a total resistance of approximately 0.01 ohm, or a total power loss of 20% in an overall array resistance of 0.05 ohm. Coaxial cable was utilized to eliminate pulse distortion and losses caused by inductance in parallel conductors.

Field strengths listed in volts per meter are averages based on measured electrode-to-electrode values and separation distance between electrodes rather than an in situ field strength

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[4] Smith Research and Development Company, Lewes, Del.

measurement, because the density of an electrical field in seawater is not uniform. For ease of measurement, the electrode-to-electrode voltage was measured at the output of the pulse generator and did not take into account cable and connection losses. Also, due to the hookup restriction in the research vessel's instrumentation room, short lengths of parallel conductors were utilized, resulting in a 40% total cable loss. Therefore the true electrode-to-electrode voltages and average field strengths are related to measured values as follows:

A. 150 V = 90 V electrode to electrode = 22.5 V/m.
B. 120 V = 72 V electrode to electrode = 18.0 V/m.
C. 90 V = 54 V electrode to electrode = 13.5 V/m.
D. 60 V = 36 V electrode to electrode = 9.0 V/m.

The configuration of the electrical field at a pulse generator output of 120 V along with actual measured field strengths (expressed as voltage drops measured across 10 cm) at various positions within the field are shown in Figure 2A. The measurements are fairly close in value but not exact. The pickup probe was attached to a long pole and the measurements taken from the side of the RV *George M. Bowers*. Because of water current and boat movement, it was difficult to hold the probe parallel to the electric field in exactly each position shown.

Laboratory tests indicated a field strength of about 15 V/m was required to properly produce electrotaxis in fish 10 cm long. Field strengths throughout the volume of water within the electrode envelope could be maintained equal to or greater than the 15 V/m requirement.

Based on initial field tests, the general zones of fish response produced by the electrode array are 1) effective control, 2) possible control, depending on fish size and its orientation, and 3) fright zone (Figure 2B). The zone of control also extends to the back side of the positive electrode.

RESULTS

Captured Fish

Voltage, pulse width, and rate are equally important for controlling the species tested (Figures 3-5, Table 1). Comparison between the pulse widths indicates that a higher percentage of experimental animals were controlled at the wider pulse widths (0.8 ms). The lower and intermediate stimulation voltages (60 and 90 V) were not as effective in controlling the animals as the higher voltage (120 V). Furthermore, the combination of 0.8 ms pulse width with 120 V appeared to be adequate for inducing electrotaxis at the widest range of pulse rates (20 to 35/s).

The ideal pulse rates for inducing electrotaxis varied for each species. Spanish sardines and scaled sardines were under good control at 20 to 35 pulses/s and round scad at 25 to 35

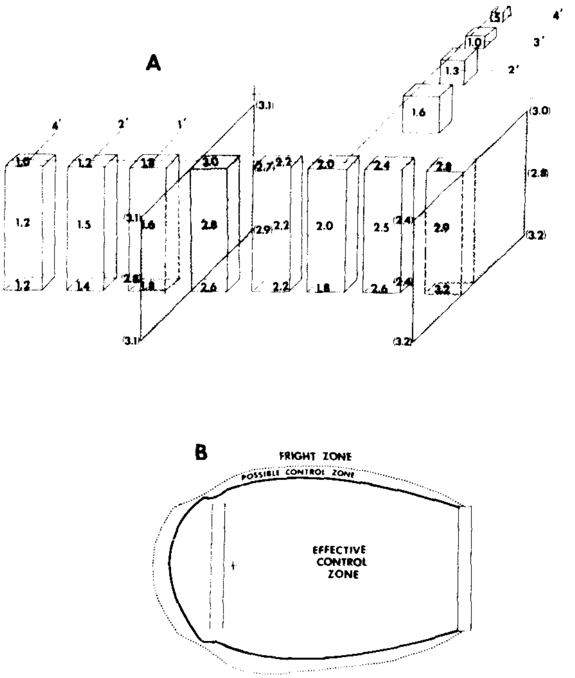

FIGURE 2.—A. Field strength configuration at 72 V electrode to electrode. B. General zones of fish response.

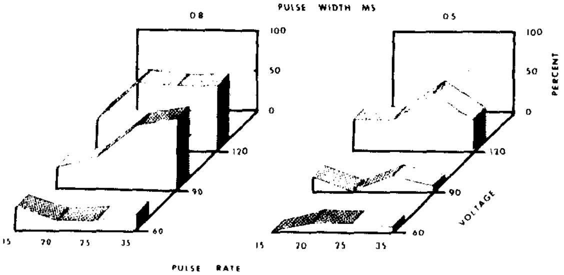

FIGURE 3.—Percent positive response of scaled sardines to various combinations of voltage, pulse rate, and pulse width.

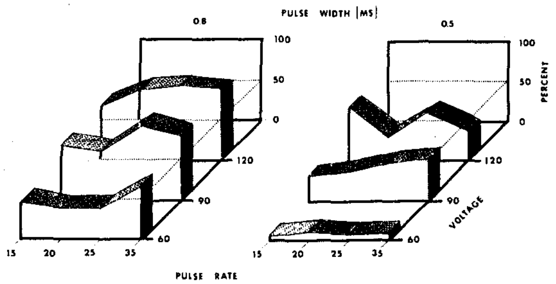

FIGURE 4.—Percent positive response of Spanish sardines to various combinations of voltage, pulse rate, and pulse width.

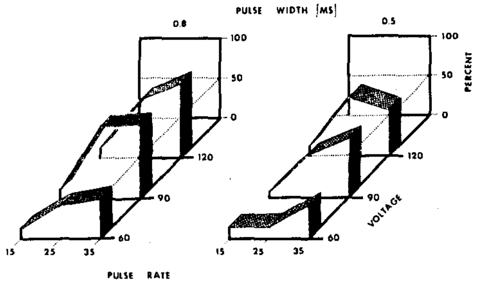

FIGURE 5.—Percent positive response of round scad to various combinations of voltage, pulse rate, and pulse width.

TABLE 1.—Percent of thread herring and bumpers at various stimulation parameters. Each observation consisted of 15 individuals except where noted.

	Pulse rate			
	Thread herring			Bumper
Voltage and pulse width	15	25	35	25
60 V; 0.5 ms	56	53		[1]50
90 V:				
0.3 ms	20	67		
0.5 ms	[2]61	63		80
0.8 ms		100	85	
120 V:				
0.3 ms	27	47		
0.8 ms	41	67		75
150 V; 0.3 ms	33	53	73	

[1] 7 individuals.
[2] 31 individuals.

pulses/s. Based on the limited data for thread herring and bumper, the best pulse rates were 25 to 35 pulses/s.

A factorial analysis was used to determine the most effective combination of pulse rate, width, and voltage for controlling Spanish sardines, scaled sardines, and round scad (Table 2). This analysis demonstrates that selection of the proper level of voltage, pulse width, and pulse rate are clearly important for controlling these species. Another important aspect may be the interactions between the three main effects, although the meaning behind this significance is uncertain. It can be seen from Table 2 that these interactions vary between species. Interdependence was observed for all tested electrical combinations in scaled sardines and Spanish sardines. Surprisingly, this was not observed for the round scad. Voltage and pulse rate interact for scaled sardines and round scad.

General observations for the first (captured) group of fish indicated if the electrical combination was not adequate, these fish would immediately escape to the side or towards the cathode. However, at times when the pulse width was 0.3 ms, thread herring would elicit a jump and skip on the surface of the water and dart out of the field. This escape behavior was never observed at the wider pulse widths. Controlled fish would swim to the anode and circle between the plates of the electrode from the inside of the field to the back of the field and back again in a circular swimming motion, and were held until the power was turned off.

The most effective electrical combinations for each species are listed in Table 3. We felt that if 70% or more of the experimental group responded positively, the combination was effective. Output voltages of 60 V or less were ineffective for controlling fish regardless of the pulse rate or pulse width. Effective fish control required an output voltage of at least 90 V with a pulse rate of 25 or more, and except for bumper the pulse width had to be 0.8 ms. An overall effective electrical combination was 120 V at 25 to 35 pulses/s at 0.5 to 0.8 ms, and 90 V at 25 to 35 pulses/s at 0.8 ms.

Wild Fish

The second group of fish was attracted into the electrode configuration by a surface nightlight positioned above the electrodes and then stimulated. Usually we were successful in attracting sufficient quantities of fish to evaluate a specific combination of electrical parameters. However, their exact position between the electrodes was never the same, especially when a large school of 30 to 50 fish were positioned between the electrodes. We only used electrical field characteristics which appeared to be successful during our daytime experiments with individual captured

TABLE 2.—Multivariant analysis of variance to determine which parameters are most useful to control Spanish sardine, scaled sardine, and round scad with probability levels (* significant at $P = 0.15$; ** significant at $P = 0.05$).

	Spanish sardine				Scaled sardine				Round scad			
Source of variation	Degrees of freedom	Mean square	F	Level of significance	Degrees of freedom	Mean square	F	Level of significance	Degrees of freedom	Mean square	F	Level of significance
Voltage	2	6,172.8	24.92	0.001**	2	8,827.1	36.25	0.001**	2	3,970.5	34.83	0.001**
Pulse width	1	17,328.0	69.95	0.001**	1	8,938.0	36.71	0.001**	1	2,809.0	24.64	0.001**
Pulse rate	3	578.1	2.33	0.099*	3	1,263.7	5.19	0.007**	2	8,149.5	71.49	0.001**
Voltage/pulse width	2	15.8	0.06	0.939	2	1,508.8	6.19	0.007**	2	110.6	0.97	0.398
Voltage/pulse rate	6	360.2	1.45	0.236	6	491.3	2.02	0.103*	4	633.1	5.55	0.004**
Pulse width/pulse rate	3	104.3	0.42	0.740	3	574.9	2.36	0.097*	2	50.6	0.44	0.648
Voltage/pulse width/pulse rate	6	496.5	2.00	0.105*	6	494.6	2.03	0.101*	4	435.7	3.82	0.020
Error	24	247.7			24	243.5			18	114.0		

TABLE 3.—Effective electrical combinations based on a minimum of 70% eliciting a positive response (Group 1 fish).

Species	Volts	Pulse rates	Pulse width
Spanish sardine	90	25-35	0.8
	120	20-35	0.8
Round scad	90	25-35	0.8
	120	25	0.5
	120	25-35	0.8
Scaled sardine	90	25-35	0.8
	120	25	0.5
	120	20-35	0.8
Thread herring	90	25-35	0.8
Bumper	90	25	0.5
	120	25	0.5

fish. The wild fish were only exposed to a pulse width of 0.5 ms, as the time between tests did not permit a change in pulse width. Since this pulse width provided satisfactory results, we felt that either 0.5 or 0.8 ms would be satisfactory, as indicated from our captured fish experiments. Visual observations indicated that the larger fish (>10 cm) reacted more quickly and swam to and from the anode before the smaller fish (<10 cm) did. Table 4 provides details and summaries of our nighttime observations with wild fish. In general, Spanish sardines and round scad were controlled adequately at 120 V and a pulse rate of 25 to 35 pulses/s at a pulse width of 0.5 ms. When large schools were attracted between the electrodes, it was not always possible to control all of the animals. Our visual observations indicated that fish in the fringe area would escape since the voltage gradient was insufficient to control fish in the fringe areas. The number of fish escaping probably varied with their position in the electrical field and their size, since smaller fish require higher voltage gradients for control than large fish. At 35 pulses/s and 120 V, we were able to pull or force fish into the electrode array from the back side of the positive electrode. Positive reactions were elicited in all species at the prime voltage of 120 and pulse rates between 25 and 35. The results from the wild fish experiment conclusively demonstrate that coastal pelagic fish of the species tested can be controlled and led with combinations of 120 V, 25 to 35 pulses/s, and a pulse width of 0.5 ms.

DISCUSSION

Effective electrical combinations for controlling coastal pelagic species determined during our field experiments compared favorably with the parameters determined by Klima (1970) in labora-

TABLE 4.—Responses of wild fish attracted to electrode configuration at preselected electrical combinations (pulse width — 0.5 millisecond).

Species	Approximate school size	Volts	Pulse rate	Reactions
Spanish sardine, round scad and bumper	10-15	120	25	Positive; pulled into anode and held.
Spanish sardine, round scad and bumper	10-15	120	35	Positive; pulled into anode and held.
Spanish sardine and round scad	30-50	120	35	Positive 50 to 90% led to anode and held; only fish in fringe area escaped.
Thread herring and bumper	5-8	120	35	Positive; led to anode.
Spanish sardine	10	90	15	3 had positive response.
Spanish sardine and round scad	10	100	50	Turn fish to anode—all escaped.
Spanish sardine and round scad	10	100	25	Turn fish to anode—all escaped.
Round scad	20-40	120	35	Positive and held at electrode.
Blue runner, *Caranx crysos*	15	120	25	Positive and held at anode.
Blue runner	10	120	35	Positive and held at anode.
Blue runner	30	120	35	20-25 positive response and held at anode.

tory studies. The range of pulse widths was slightly narrower in the field than in the laboratory where the experiment tank maintained a uniform field, test animals could not escape, and in which narrow pulse widths were not possible. Since wide pulse widths require more electrical energy, it is desirable to select the narrowest pulse width possible which will allow proper control of the species. This in situ investigation clearly demonstrates that pulse widths between 0.5 and 0.8 ms can be effectively employed in open water situations in conjunction with proper field strengths and pulse rates. Our results demonstrate that the effective control of the fishes tested requires no less than 15 V/m at pulse widths of 0.5 ms or greater and pulse rates ranging between 20 and 35/s. A pulse width of 0.3 ms was completely ineffective within the proper field strength and pulse rate range used in our experiment.

A review of the field test data suggests an additional parameter, minimum pulse control power for a specific pulse width and field strength, should be determined during future field experiments. Obviously a minimum output voltage and current is necessary to maintain the established 15 V/m in any particular electrode configuration and resulting load resistance. However, once the minimum power to maintain 15 V/m is reached, if future research can establish that a pulse envelope of minimum total power within a minimum and maximum set of values for pulse rate and pulse width is the important criterion for proper fish control, much greater latitude would be possible in designing a pulse generator for a particular fishing system. This would permit a designer to better select pulse rate, pulse width, and maximum values for voltage and current to provide better equipment reliability and possibly cheaper construction.

The power required to control fish is presented in the following discussion based on the parameters of pulse width, pulse rate, and field strength which we used as criteria during the field tests. Power for each pulse (P_p) is described as:

$$P_p = V_e \times I \times P_w \qquad (1)$$

where V_e = electrode voltage
I = current at load resistance in amperes
P_w = pulse width, milliseconds.

The total load resistance equaled 0.05 ohm with an electrode-to-electrode resistance of 0.033 ohm and a cable loss of 0.017 ohm. Slight daily variations of 0.006 ohm were noted in electrode-to-electrode resistance due to small changes in salinity and temperature. For computations, we rounded the resistance values slightly and the electrode-to-electrode voltage was established as 60% of the output voltage. The current (I) and electrode-to-electrode voltage (V_e) at selected output voltages using an array resistance of 0.03 ohm and a loss resistance of 0.02 ohm were:

Output voltage	V_e	I
150	90	3,000
120	72	2,400
90	54	1,800

The total power (kW) delivered into the electrode array after cable losses can be computed as follows:

$$P_t = V_e \times I \times P_w \times P_r \qquad (2)$$

where P_r = pulse rate, pulses per second
P_t = total power in kilovolt ampere.

Using the above values, the total power for effective electrical control values used was:

V_e	P_r	P_w	P_t
54	25	0.8	1.94
72	25	0.5	2.16
72	25	0.8	2.77
90	35	0.3	2.84

The preceding results suggest there is a minimum requirement of total power *(P_t)* to properly control the fish which would be a constant regardless of the specific combinations of pulse width, pulse rate, and field strengths. Once the effective field strength of 15 V/m is exceeded, it appears that different minimum values of pulse rate and pulse width can be obtained to produce equally effective fish response. Unfortunately, there are too few data points to support this conclusion. To properly substantiate such a hypothesis, we would have to determine either a minimum pulse width for a constant electrode voltage at each pulse rate or a minimum pulse rate for a constant electrode voltage at each pulse width. Without this, we cannot definitely state that a parameter of total power *(P_t)* can be used as a control specification rather than various combinations of electrode voltage, pulse width, and pulse rate. Many more tests would be needed to substantiate the hypothesis, although this approach would be advantageous from a designer's standpoint.

120-kVA Pulse Generator Design

The primary objective in the design of our pulse generator was to produce a system which, based on the results of the 12-kVA pulse generator electrical fish control experiments, would provide the capability for prototype development and effective harvest of fish in several modes of system operation. The output power of the pulse generator and pulse control characteristics were established to satisfy requirements for automatic fish harvesting without nets (Klima, 1970), electrical mid-water and bottom trawling for fish, and to provide the potential for prototype development of possible future applications such as fish barriers, electrical aquaculture cages, or other such applications.

Netless Fish Harvesting Mode

The initial reason for our development efforts in the field of electrical fishing was to eventually achieve the automatic fish harvesting system. Since this application imposed the most serious power demands, the design specifics were established around that set of conditions and results of this study were used to calculate the power requirements for a netless fishing system. Allowances were made, however, for application of the system to other electrical control applications. One, a mid-water trawl mode, is described later in the paper.

Use of lights at night concentrate fish (Wickham, 1971) in a volume of water which can then be electrified. The minimum volume of water within a light field which needs to be effectively covered electrically to produce commercial quantities of fish would be 5 m in cross section and 10 m in length. An equation for resistance of seawater between the electrodes is:

$$R = \frac{\rho L}{A} \qquad (3)$$

where L = distance between electrodes in meters
A = surface area of the electrodes in square meters
ρ = resistivity of seawater in ohm-meters.

According to this equation the load resistance of two parallel plates is:

$$R = \frac{0.213 \times 10}{25} = 0.0852 \text{ ohm}$$

where ρ at 30‰ and 24°C = 0.213 ohm-m.

However, this formula only describes the resistance of the volume of water between two electrodes as if the electrode array was a finite conductor. In actual practice, a significant spreading of the electrical field occurs in seawater. If the size of an electrode is small in comparison to the separation distance, the configuration of the electrode in the array is the principal factor in determining the resistance value, as would be the case with small balls or cables for electrodes. For our situation, the size of the electrodes and separation distance are equally important. Since the load resistance of the array in seawater is extremely low, the resistance value used to calculate power requirements becomes extremely important. A small error in the resistance could result in a large miscalculation of the necessary power requirements. For this reason we took great care in computing resistance accurately. Resistance measurements for this situation can be calculated by two methods referred to as Kreutzer and empirical technique. Kreutzer developed a formula for calculating spread resistance for one electrode:

$$R_s = \frac{K_o\,(1 + T \times 0.02)}{\sqrt{A}} \tag{4}$$

where R_s = spread resistance of one electrode, including field fringing
K_o = a constant at a specific salinity
T = temperature in centigrade
A = area, square meters.

(C. Kreutzer, pers. commun.) The constant K_o varies with different salinity values and must be recalculated for each new salinity. It can be obtained by solving for K_o in Equation (4) which requires knowledge of resistance, surface area, and temperature. Once the value of K_o is determined for a specific salinity, Equation (4) can be used to calculate R_s for varying electrode surface areas. Because the value of K_o varies with different salinity and is difficult to determine since in situ resistance measurements are required, we decided to establish an empirical ratio which compares the theoretical calculated resistance from Equation (3) to an actual measured electrode resistance. The calculated resistance according to Equation (3), using the 2 × 2 × 4 m electrodes of one test was:

$$R = \frac{0.189 \times 4}{4} = 0.189\,\text{ohm}$$

with a salinity of 32.9‰ and a temperature of 28.7°C (ρ = 0.189 ohm-m). The measured resistance was actually 0.039 ohm. An index of difference between the calculated and measured resistance provides a ratio of 4.85. The ratio of calculated to measured resistance ranged from 4.85 to 5.2 throughout the study period, with the measured resistance of the electrode array varying from 0.035 to 0.04 ohm. Hence, a midrange value of 5.0 seems the most practical and resistance value one-fifth of the Equation (3) calculated value is used to compute total spread resistance as shown in the following equation:

$$R_t = \frac{\rho L}{5A} \tag{5}$$

where R_t = total spread resistance including both electrodes.

As a cross-check to Equation (5) we also computed the spread resistance from Equation (4) using a value of K_o derived from the sample test. The measured resistance of the electrode array in seawater was 0.039 ohm. Since each electrode contributes one-half the resistance, the spread resistance for Equation (4) is 0.0195 ohm. In addition, since both sides of each electrode in our tests were exposed, the surface area for the equation is twice that of one side. Using these values, K_o is determined to be:

$$0.0195 = \frac{K_o(1 + 28.7 \times 0.02)}{\sqrt{2(2)^2}}$$

where K_o = 0.035 ohm-m.

For a 5 × 5 × 10 m electrode array using Equations (4) and (5), the following load resistances are determined at 28.7°C and 32.9‰:

Equation (4)

$$R_t = \frac{0.189 \times 10}{5(5)^2} = 0.01512\ \text{ohm},$$

Equation (5)

$$R_s = \frac{0.035\,(1 + 28.7 \times 0.02)}{\sqrt{2(5)^2}} = 0.00779,$$

where $R_t = 2R_s = 2(0.00779) = 0.01558$,
$R_t = 2R_s$ since R_s is the resistance of one electrode.

As can be seen, the value for the load resistance of a 5-square meter by 10-m array compares favorably when determined by the two different equations. The higher value of 0.01558 ohm was used in making power calculations since any electrode array will have some additional resistance due to connection losses.

Results from our field study thus provided the following set of basic design specifics for our prototype pulse generator for use with attracting lights in a netless fish harvesting application:

1. Minimum field strength – 15 V/m.
2. Pulse rate – 20-35 pulses/s.
3. Pulse width – ≥0.5 ms.
4. Array size – 5 × 5 × 10 m.
5. Load resistance of array – 0.01558 ohm.

Using these specifications, we determined the output capability of the pulse generator which would satisfy our requirements by the following equation:

$$P = VI \times fl \tag{6}$$

where P = power, watts
V = output voltage, volts
I = current, amperes
f = pulse rate, pulses per second
l = pulse length or width, seconds.

To insure an adequate field strength throughout our electrode array, we chose a value of 20 V/m for the power calculations. We also selected a maximum pulse rate of 50/s and pulse widths of 0.5, 0.75, and 1.0 ms to give the pulse generator more versatility. Using Equation (6), the power requirement is:

$$V = 20 \times 10 = 200 \text{ V for 10-m array}$$

$$I = \frac{V}{R_t} = \frac{200}{0.01558} = 12{,}837 \text{ A},$$

and at 50 pulses/s and 0.75 ms pulse width

$$P = (200)(12{,}837)(50)(0.75 \times 10^{-3})$$
$$P = 96{,}278 \text{ W}.$$

In an applied system, a cable and connection loss will be experienced. Because of the very low load resistances of seawater, a 25% cable loss can easily be expected. Rounding off our requirement to 90 kVA and after allowing for a 25% loss, we need a pulse generator of 120-kVA output to satisfy the system requirements we established.

As a crosscheck of the above designed system, the following formula (Kreutzer, 1964) is used to calculate the effective fish control range of one electrode:

$$R = \sqrt{\frac{I \times L \times \rho}{G \times 2 \times \pi}}$$

where R = effective range, meters
I = current into the water, amperes
L = length of fish, meters
ρ = water resistivity, ohm-meter
G = body voltage of fish.

To determine the effective range of 20 V/m, a value of 1 m is used for the fish length, fish body voltage is 20 V, and the resistivity is again 0.189 ohm-m.

Allowing a 25% cable loss requires a total input voltage of 267 V at a total load resistance of 0.0208 ohm, and the current in the water is found to be:

$$I = \frac{V}{R} = \frac{267}{0.0208} = 12{,}837 \text{ A}.$$

Using these values, range (R) is found to be:

$$R = \sqrt{\frac{12{,}837 \times 1 \times 0.189}{20 \times 2 \times 3.14}}$$
$$R = 4.40 \text{ m}.$$

Since this value is computed for one electrode, the 20 V/m range of two electrodes will be 8.8 m. In actual practice, however, the range of two electrodes paired together is greater than twice the reach of one, and we can supply a 5 × 5 × 10 m array with 20 V/m. At our minimum specification of 15 V/m, the calculated reach of one electrode is 5.08 m.

Since the configuration of the electrode array determines array resistance, various combinations of electrode size and separation distance can change the pulse voltage and current requirements. For this reason, a certain degree of flexibility was designed into the netless fish harvesting mode of the pulse generator. The system is capable of delivering up to 1,000 V to an electrode array. However, at this voltage, the array shape has to be changed to produce a much higher load resistance to maintain the current at a value which is within the 120-kVA rating of the system and the current and voltage carrying capability of various components in the unit. For instance, at 1,000 V the electrode array has to have a total resistance of 0.3 ohm.

Mid-Water Trawling Mode

The pulse generator was also designed for application to electrical trawling. This use of the system requires a significantly different configuration than in netless harvesting. Since the pulse generator components are far too large to consider underwater mounting of the system on a trawl, it was necessary to design the unit for operation through a long power cable. The cable transmits the pulsed power from the vessel to the trawl. A cable length of 2,200 feet (670.1 m) was chosen to allow trawling to depths of 100 fm (fathoms) (182.9 m) with a cable to depth ratio of at least 3:1. The length of the cable is important because as it gets longer its direct current resistance increases and therefore either the cable losses become greater or the size of the conductors has to be increased to prevent excessive losses. Since a large power loss is not acceptable, conductor size and the resulting cable diameter eventually become too large and are limiting factors in the total length and therefore the power then can be transmitted down the cable.

The operation of a pulse generator into a long cable requires careful design in order to work. First, the impedences of the pulse generator, cable, and electrode array have to be properly matched through step-up and step-down transformers to accomplish transmission of the pulse down the cable. Unless impedences are properly matched, the pulse will become very distorted or can be totally lost in the cable. Another serious limiting factor in the operation of a pulse generator through a long cable for trawling is the underwater transformers which match the power supply cable to the electrode array. The delivery of significant levels of power, such as 120 kVA, through a single transformer would require a transformer that is quite large and would weigh several hundred pounds to handle the pulse current into an array with a load resistance of 0.05 ohm.

Our first intended application of the pulse generator in a trawling mode was with a mid-water trawl. The standard mid-water trawl being used at the Pascagoula Laboratory was a net that opened approximately 9 × 9 m under water. In actual field measurements, it has been found that the net generally opens between 7.5 and 9.0 m in height. Therefore we required the pulse generator to accomplish effective electrical trawling on a vertical opening of 7.5 to 9.0 m and a horizontal opening of approximately 9.0 m. In the mid-water trawl application we expect the electricity to provide a combination of fright, leading, and some tetanus to aid in harvesting of fish. Past experiments at the Pascagoula Laboratory demonstrated that fish generally accumulate in the mouth and forward body of the trawl. Therefore an electrical field applied periodically should force the fish back into the cod end.

Because of component ratings, loading of underwater transformers, and design restrictions, a power of 80 kVA was chosen as the maximum which could be supplied to our electrode array in a mid-water trawling mode. Since the application of 80 kVA through a single transformer is difficult under water, we chose four electrode pairs and four underwater transformers matched to each electrode pair to cover the 9.0 × 9.0 m net. It was found that a reasonable electrode size could be used which would provide a load resistance of 0.2 ohm for each pair and deliver 20 kVA from each transformer. This meant that by connecting the electrode pairs in parallel, each transformer would carry one fourth the current which would be required of a single transformer at the same total output. In addition, the four parallel electrode pairs would represent a total load resistance of 0.05 ohm which could easily be matched to the other impedences of the system.

Within the impedence matching requirements of the pulse generator, cable, and electrode array, and using the maximum output voltage of 2,500 V that the unit is capable of supplying in this mode, 450 V can be supplied to each electrode pair through the matching transformers. The surface area of each electrode pair must be adjusted to provide a resistance value of 0.2 ohm. Therefore, the pulse current of this condition is:

$$I = \frac{V}{R} = \frac{450}{0.2} = 2{,}250 \text{ A.}$$

Using Equation (7) at 15 V/m, the range of an electrode is:

$$R = \sqrt{\frac{2{,}250 \times 1 \times 0.189}{15 \times 2 \times 3.14}}$$

$$R = 2.13 \text{ m.}$$

However, to accomplish at least a fright reaction required 10 V/m or less, depending on fish size. We feel that a fright reaction, although not as effective as positive control of fish, will accomplish disorientation and therefore harvest of some fish in an electrical trawling mode. Since the temperature of below-surface water will be colder, we can use higher resistivities than 0.189 in calculations as shown in the following calculation for field reach at 100 fm water depth. In addition, Kreutzer's Equation (7) states that the factor in the denominator goes from 2 to 4 as the electrodes are placed in mid-water. Using these values, we calculate the maximum variation of values from the surface to 100 fm in the 10 V/m range of one electrode to be:

Surface:

Salinity $32.9^{0}/_{00}$, temperature 28.7°C, $\rho = 0.189$

$$R = \sqrt{\frac{2{,}250 \times 1 \times 0.189}{10 \times 2 \times 3.14}}$$

$$R = 2.60 \text{ m.}$$

100 fm:

Salinity $30^{0}/_{00}$, temperature 10°C, $\rho = 0.3$

$$R = \sqrt{\frac{2{,}250 \times 1 \times 0.3}{10 \times 4 \times 3.14}}$$

$$R = 2.32 \text{ m.}$$

Again, the range of two electrodes is found to be greater than twice the range of one electrode. In addition, since each electrode pair based on their required size for 0.2 ohm, will be separated by about 1.22 m, field strength adding will occur. Therefore, the effective range of an electrode pair is significantly more than twice the range of one electrode. By installing one polarity electrode on the headrope and the opposite on the footrope, we should be able to cover a 9 × 9 m area with the weakest part of the field having at least enough strength to frighten fish. We can also use pulse rates higher than 35/s, which will immobilize fish more rapidly. In addition, it must be remembered that at distances closer to the electrodes, the field strength increases and reaches values which will effectively lead or stun the fish. Because the size of each electrode is relatively small, current densities capable of stunning fish will be found at some minimum distance from the electrodes. This is not desirable for leading fish in a netless harvesting application and is avoided by using large electrodes, but it is very desirable in a trawling mode where the electrodes are inside the body of the net.

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