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RESPONSE OF SALMONIDS TO LOW FREQUENCY SOUND

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THE construction of dams in the Columbia River system for the production of hydroelectric power has created numerous problems for anadromous fish. Some of the difficulties relate to the loss of juveniles migrating downstream, which are unable to find their way through reservoirs or are injured as they pass through turbines or over spillways. In an effort to prevent this loss, the Bureau of Commercial Fisheries has been studying various methods of guiding these fish into collection facilities for passage around hazardous areas. This paper reviews past and current research on the use of sound as a method of guiding downstream migrating salmonids.

Burner and Moore (1953) exposed rainbow *(Salmo gairdneri)* and brown trout *(S. trutta)* to sounds between 67 Hz and 70,000 Hz at intensities up to 82 dB re 1 microbar. Moore and Newman (1956) conducted a similar study exposing juvenile salmonids to frequencies between 50 Hz and 20,000 Hz at intensity levels up to 7200 dynes/cm^2. These authors concluded there was no significant response to sound except for an initial "start" at the lower frequencies.

The California Department of Fish and Game* conducted a field study in which juvenile chinook salmon *(Oncorhynchus tshawytscha)* and striped bass *(Roccus saxatilis)* were guided into a bypass channel using a sound barrier constructed of 3- by 4-ft steel plates with air-driven vibrators attached.The number of fish entering the bypass increased from 52 per cent without sound to 90 per cent with sound for chinook salmon fingerlings and from 59 per cent to 80 per cent for juvenile striped bass. Subsequent attempts by Painter to guide fish in a river using a similar device were unsuccessful.

* Personal communication from Richard Painter, California Department of Fish and Game, 1963.

In 1964 we attempted to guide steelhead trout *(Salmo gairdneri)* migrating downstream by using a sound barrier similar to that used by Painter. The study was made in an eastern Oregon irrigation canal that was divided into two channels, one 5 ft wide and the other 10 ft wide. The 5-ft channel served as a bypass when the barrier was in. The barrier (Fig. 1) was installed upstream from the 10-ft channel. It consisted of ten 3- by 4-ft steel plates mounted vertically and parallel to the flow of water. Air-driven vibrators were attached to alternate plates. These vibrators were driven at 270 Hz during the testing period. The frequency and amplitude of the sound generated by these vibrating plates were not measured. Painter

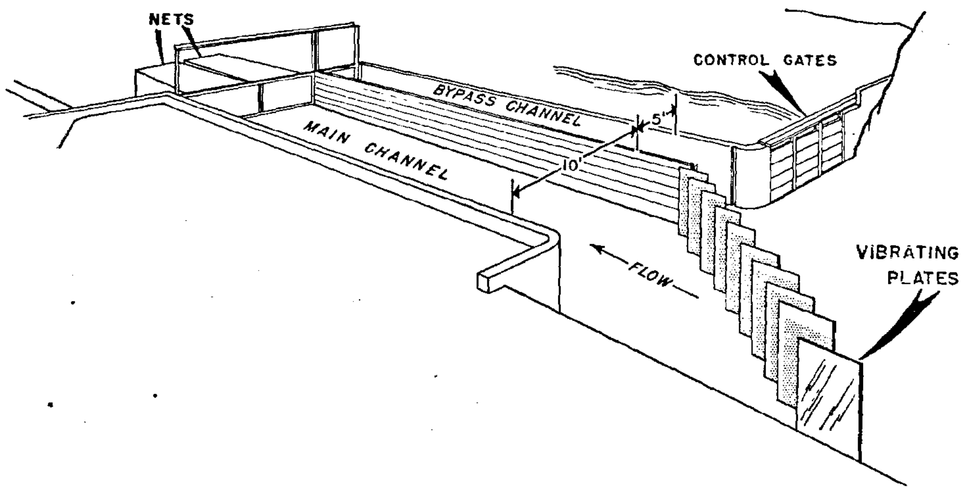

FIG. 1. Sound barrier system and evaluation facilities in irrigation canal near Umatilla, Oregon.

measured the acoustic pressure 1 ft upstream from his installation and recorded an intensity of 97 dB re 0.0002 dynes/cm^2 falling off to 91 dB at 11 ft.

Before the sound barrier equipment was installed, 11 per cent of the steelhead migrating down the canal had entreed the 5-ft channel. After the installation, the number of steelhead entering the two channels was recorded for periods with and without vibration. An average of 77 per cent of the fish migrating through the canal during tests with vibration entered the 5-ft bypass channel, whereas only 33 per cent entered the bypass when the vibrators were off. The difference between the 11 per cent entering the 5-ft channel before the sound barrier equipment was installed and the 33 per cent after it was installed was probably due to the flow pattern created by the plates and to some extent by their guiding angle.

Following this field study, several laboratory experiments were conducted under a contract with the Boeing Company at Seattle, Washington. Juvenile chinook salmon were exposed to low frequency sounds of known frequency and intensity. The objectives of these experiments were to determine the frequency range in which the fish would respond, to measure the intensity necessary to elicit a response, and to describe the characteristics of the response.

These studies were conducted in two phases. In phase one, fish were placed in a sealed tank attached to an electromagnetic vibrator which was vibrated at various frequencies between 15 and 500 Hz. In phase two, fish were exposed to sounds between 5 and 500 Hz in an open channel with flowing water.

PHASE ONE STUDIES

Experimental Apparatus

The experimental apparatus for phase one consisted of an aluminium and plexiglass test chamber (Fig. 2) and an electromagnetic vibrator (force rating 7500 lb; maximum acceleration 100 *g*). The experimental chamber was mounted on a thick magnesium plate attached to the vibrator. The direction of vibration was horizontal and parallel to the long axis of the tank. Two pressure-sensing transducers were used to monitor the pressure

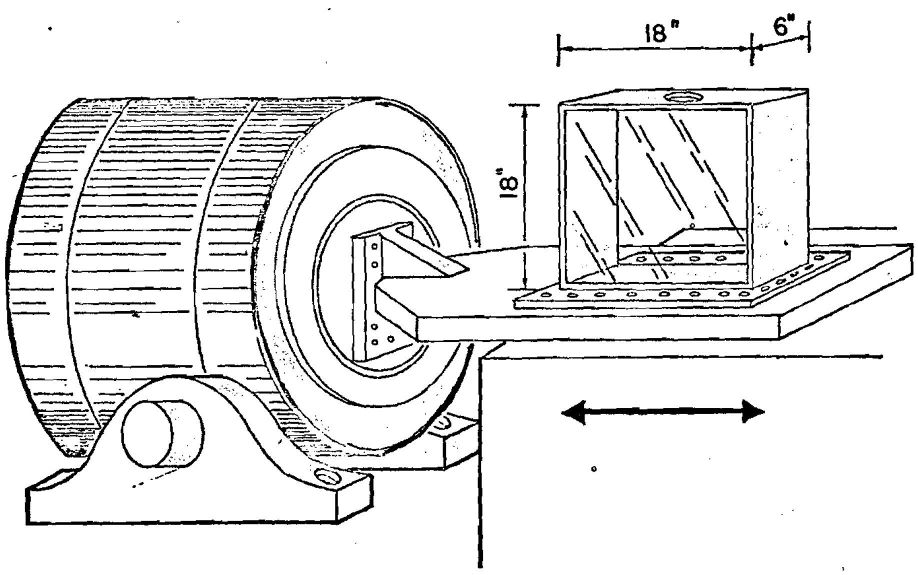

FIG. 2. Electromagnetic vibrator and test chamber. Arrow indicates line of vibration.

inside the chamber. An accelerometer was attached to the face plate of the vibrator to monitor the frequency and intensity of the vibration. The maximum acceleration used during these tests was 5 *g*.

Test Method

For each test the tank was filled with fresh water, after which five fish were introduced and the tank closed. No air was present in the tank during tests. Fish were held in the tank for 15 min before the vibrator was turned on. The response of fish to the specific frequencies and amplitudes were then noted. At the completion of each test, the exposed fish were removed; fresh water and non-exposed fish were then introduced for testing at another frequency. The dissolved oxygen content of the water in the test chamber was measured before and after each test. The minimum oxygen value recorded was 8 parts per million (ppm).

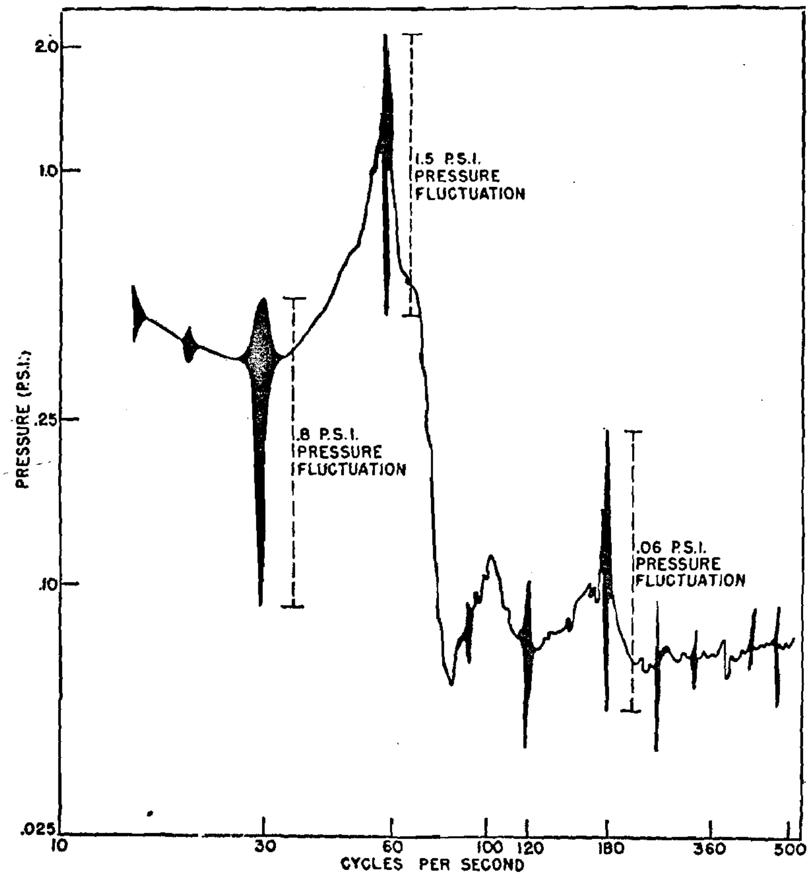

FIG. 3. Pressure within test chamber at frequencies from 15 to 500 Hz. Note fluctuation around 30, 60, and 180 Hz.

Observations

We noted two types of response. In one type, fish showed a loss of equilibrium, interrupted by short periods of erratic swimming. Characteristically, fish swam either on their sides, upside down, straight up or straight down, and often ran into the walls or into other fish. This loss of equilibrium occurred at an input of 30, 60, and 180 Hz with a 3 *g* acceleration; it was associated with a wide fluctuation in the pressure within the tank (Fig. 3). At an input frequency of 60 Hz, pressure fluctuated approximately 100 times per minute over a range of 1.5 lb/in^2.

We described the second response as an escape action which was characterized by rapid swimming around the tank. Frequently the fish would place their snouts against the bottom corners of the tank and try to swim through the wall. The escape response was noted at several frequencies and at several acceleration levels; it was most pronounced at 70 and 88 Hz at an acceleration of 3 to 5 *g*. Fish exposed to these conditions would continue to swim until exhausted.

PHASE TWO STUDIES

Phase two studies were conducted in an open test channel with flowing water.

Experimental Apparatus

The wooden test tank (Fig. 4) consisted of two parts—a rectangular, endless raceway and attached anechoic chambers. The test portion of the raceway was separated from the anechoic chambers by a $\frac{1}{8}$-in. sheet of rubber (density 1.02). The sound source was located in the wall opposite the rubber sheet. Theoretically the sound wave traveling across the channel would pass through the rubber sheet into the anechoic chambers with a minimum of reflection.

A grid was painted on the floor of the test section to enable us to describe the response of the fish in reference to fixed points within the channel. Screens were installed to confine the fish to the test area of the raceway. A pump located outside the raceway created a water velocity of $\frac{1}{2}$ ft/sec through the test section. This velocity was fast enough to cause the fish to maintain an upstream orientation but not fast enough to tire them during the testing period.

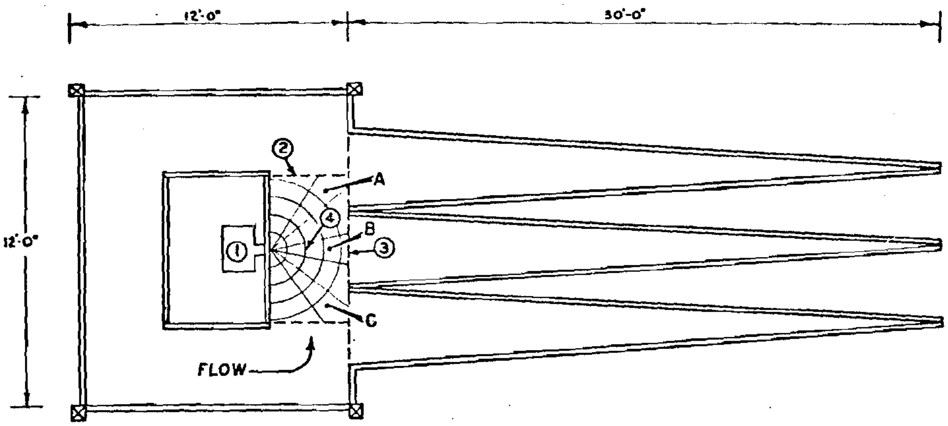

FIG. 4. Plan view of endless raceway and attached anechoic chamber. A, B, and C are areas where fish response was recorded. Note position of following: 1, Vibrator; 2, Screen; 3, Rubber sheet; 4, Location of hydrophone.

Electronic Equipment

An electromagnetic vibrator with a force rating of 2250 lb and a maximum acceleration of 100 *g* was used to generate the pure tones used for this phase of the study (Fig. 5). The vibrator was attached through a hole in the wooden wall of the test section to a 6-in. disc mounted flush

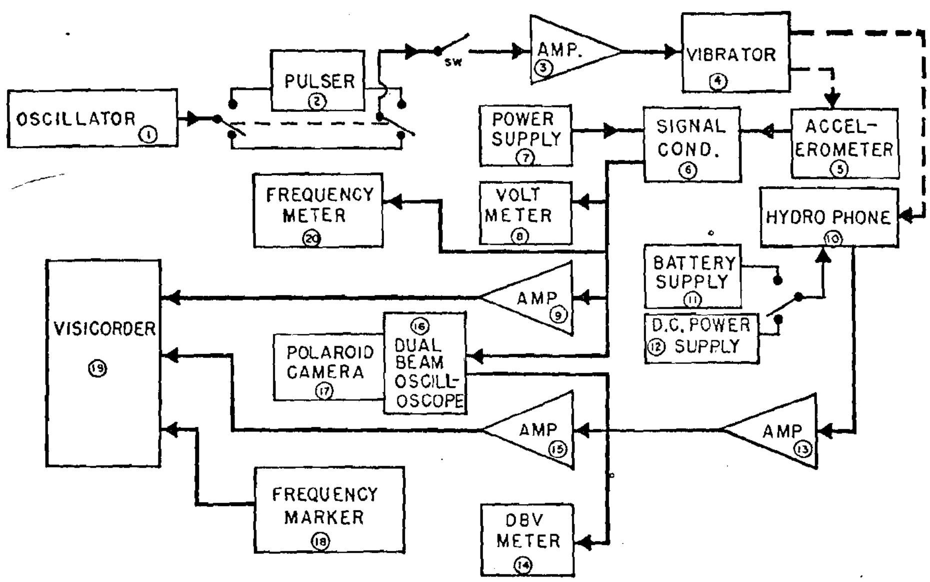

FIG. 5. Block diagram of electric system used to generate and record sounds during open-channel tests at the Boeing Company, Seattle, Washington.

with the inside of the wall and joined to it by a rubber gasket. The system was capable of generating sine waves through the test frequency band with amplitudes well above the maximum of 160 dB re 0.0002 dynes/cm^2 used during this study. A hydrophone was mounted 2 ft from the wooden wall and 18 in. above the floor directly in front of the disc. The hydrophone was kept as this reference point during all tests with fish.

Test Methods

We exposed the fish to several patterns including sine sweeps, pulsed waves, and continuous waves before a final test design was chosen. At the conclusion of these exploratory studies, we designed an experiment to test fish for habituation resulting from repeated exposure to sound and to measure the response at particular frequencies.

Each group of fish was exposed to 22 test frequencies and three reference frequencies. The selected reference frequencies were 10, 70, and 240 Hz. These were used at the beginning, middle, and end of each test. A total of five tests using 47 different frequencies was completed.

To begin a test, 200 fish were placed in the test section for a 30- to 45-min acclimation period. Then the oscillator was set at the pre-selected frequency and the gain on the power amplifier increased until the acoustic pressure at the reference point reached 130 dB re 0.0002 dynes/cm^2. This procedure required about 1 minute. The power amplifier was then switched off. After 3 min, the power was turned on for 1 min, shut off for 1 min, and then turned on for two 10-sec periods separated by a 1-min off period. The next frequency was then set and the procedure was repeated for each of the 31 selected frequencies. Response of fish during the various exposures were noted by an observer. Each of the 1-min exposures was recorded on 16 mm movie film.

To prevent biased evaluation, the order of presenting the various frequencies was randomized and was not known to the observer until the test was completed.

Data Collected

The data we collected were limited to three sections of the grid as shown in Fig. 4. During the first exposure (1 min), we noted: (1) the direction the fish swam immediately after the sound was turned on, (2) the distance they moved away from the sound source, and (3) the amount of time they stayed out of the evacuated area. During the two 10-sec exposures, the observer recorded the furthest point of response from the sound source, All responses noted were avoidance responses.

Following a preliminary examination of the data collected in the above tests, several representative frequencies were selected, and pressure levels and wave shapes were measured at 165 selected points within the test section. Pressure at the reference point was maintained at 130 dB during these measurements.

Data Assessment

At the completion of the tests, it was necessary to assign a numerical value to each response so they could be compared at different frequencies. This was done in an effort to determine which frequency might be the most effective for repelling salmonids. To do this, each of four factors was weighed according to its relative importance to a general avoidance response.

The first factor was the swimming direction after the sound was turned on. Since practically all fish reacting to the sound swam laterally away from the sound source, this factor was not considered. The second factor was the time fish remained out of the evacuated area. Inasmuch as the time factor was extremely variable between different exposures at the same frequency, this measurement was also excluded. This left two factors—the farthest distance at which fish responded to the sound source and the area evacuated by the fish when moving away from the sound source. These two remaining factors were used to evaluate the degree of response to different frequencies. This was done by listing all combinations of values that could have occurred, beginning with the one arbitrarily determined to indicate the least valuable avoidance response. The least valuable response was when the fish gave a "start" reaction at 1 ft from the sound source but did not move away from it; the most valuable response was when all fish gave a "start" and vacated an area within 4 feet of the sound source. An intermediate response was one in which fish 4 ft away gave a "start" reaction and all fish within 2 ft of the sound source evacuated that area. We then assigned a numerical value to each response equal to its position on the list. This value is referred to as the computed value of fish response.

Fish Response

The second phase studies have just been completed and we are now starting a comprehensive evaluation of the data. For the present, several generalizations can be made.

Fish responded to the onset of sound from the lowest frequency tested up to 280 Hz; above this frequency no response was noted. The highest response values computed were obtained between 35 and 170 Hz. Figure 6 illustrates the response recorded for the section of the grid marked "A". Within this range of frequencies, the greatest distance moved away from the sound source was 2 ft. This occurred at 40, 70, 80, 100, and 120 Hz. The longest period the fish stayed out of the evacuated area was 60 sec.

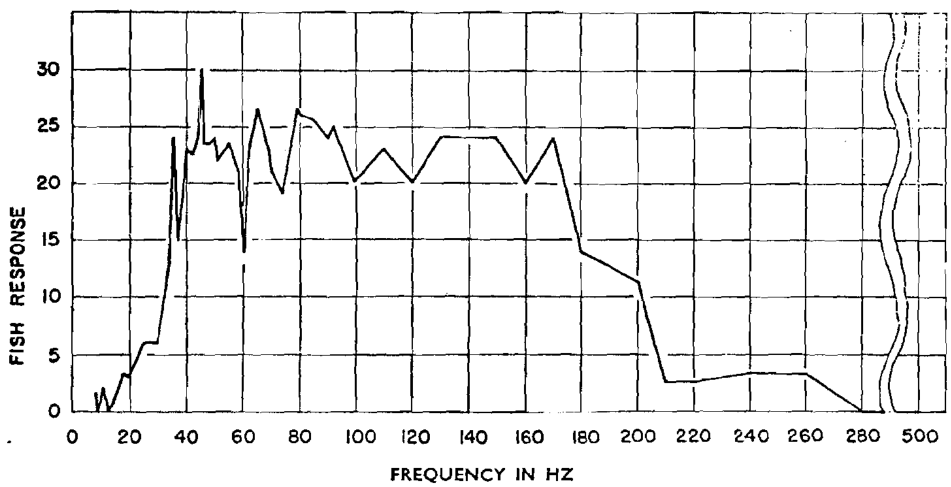

FIG. 6. Computed values of fish response to sound. Average of all data collected from section "A" of test tank.

This avoidance occurred at 80 Hz; the distance from the sound source was 2 ft. This period of evacuation was an exception; the fish usually resumed their normal distribution within 5 sec.

Our analysis of the response of fish to the reference frequencies shows that the fish did not become less sensitive due to repeated exposure.

A preliminary examination of the mapping data showed a wide variation in the intensity and form of the pressure field caused by a resonance of the wall through which the vibrating plunger was mounted and to a lesser degree by reflections. The lowest pressure was generally at the surface close to the rubber wall. An analysis of the wave shapes at different points indicated that a sine wave of the selected frequency was present in practically all areas of the tank.

Interpretation

Many attempts have been made to guide downstream migrating salmon using chemical, visual, and acoustical stimuli. None of these studies has resulted in the development of an efficient guiding system.

The results of the present studies indicates the possibility of repelling salmon with sound waves and the frequencies which may be best for this purpose.

In the field study conducted in the Eastern Oregon irrigation canal, fish responded to the sound in a way that caused them to move into the bypass. There are two theories that can explain this. The first theory assumes the fish can localize the sound and are repelled by it. If this is so, the fish would move as far away from the barrier as possible during their downstream migration and consequently move into the bypass channel. The second theory assumes the fish react negatively to the sound, but not being able to localize the source, swim to the bottom of the canal. If these assumptions are valid, the fish would have approached the barrier close to the bottom of the canal. Before we started the field study, we had recognized this possibility and had placed a 6-in. sill along the leading edge of the plate barrier. If the fish did approach the barrier close to the bottom they might have moved into the bypass channel by following this sill.

The results of the phase two study at the Boeing Company lend support to the first theory. The initial response of the fish to frequencies between 35 and 170 Hz was to swim away from the sound source; however, they would soon wander back into the vacated area. The possibility of the fish recognizing the primary source of sound within the test chamber after the first 2 or 3 sec is remote due to the many reflective surfaces within the tank.

Severe physical problems are encountered when experimenting with low frequency sound in a small tank. This makes it difficult to obtain useful information about a fish's ability to localize a sound source using the behavior study technique. Future workers should consider working in a free field environment or plan on making a major effort in the development of an anechoic test tank.

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DISCUSSION

DR. VAN BERGEIJK: The first comment that should be made on this paper is, I think, that it is an example of what I would call "biological engineering". The effort is directed primarily at solving a specific problem: how to keep fish out of generators. As such, it is partly based on common sense and good-old empiricism, and wholly unsuccessful, so far. Which should not discourage one; problems are often more interesting by virtue of being difficult.

As to specifics, it seems to me that the pressures you measure in the phase 1 experiment are actually irrelevant. If you accelerate a mass of water contained in a non-rigid container, you can't help developing pressures, of course; but from what we know about equilibrium functions it would appear that the acceleration itself is the relevant stimulus, while any pressures developing incidental to this have negligible effect. In other words, the phase 1 experiment does not demonstrate sensitivity to sound pressures, I think, but simply shows that, given sufficient acceleration, fish will become disoriented, or will exhibit signs of discomfort. Whether what you see can really be interpreted as an "escape reaction" seems a bit questionable to me without further substantiation. If it is indeed an escape reaction, the question is raised whether it could be used commercially. Here I have a crucial question: how much power is required for evoking the reaction? With the volume of water to be moved at these accelerations, you may be consuming a significant part of a generator's output!

The phase 2 experiments seem quite straightforward; the sound source generates a considerable near-field displacement, and the measured pressure, though probably proportional to the stimulus events, is a complex quantity due to the near-field pressure, the free-surface motions of the water and any residual reflections in the tank. I would suggest that the effective stimulus in this case is not the pressure but the near-field displacement (or a derivative function of it), and that the receptor organ is the lateral line. The 2 ft maximum escape-distance strongly suggests a near-field $(1/r^2 - 1/r^3)$ attenuation.

Two feet is not much distance in a fast-flowing river, but if a barrier could be constructed of these vibrators, the problem would be solved; it would be much less formidable in its power requirements than the shaking plates. But I have another suggestion,

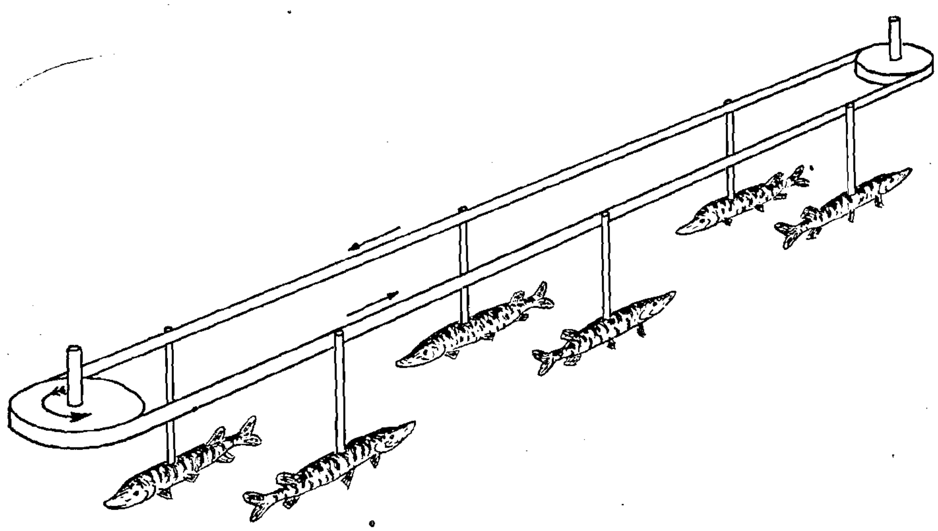

FIG. 6.

once it seems to be the case that the lateral line can be used as a channel for the communication of discouragement. Why not put some pike or muskie in wire live boxes across the channel? That way you optimally utilize the little fish's powers of recognition; the few lunkheads that don't flee will keep the pike alive. Since the logistics of keeping this sort of system working for extended periods are a bit hairy, I have thought of another system that is shown on Fig. 6. As you can see, a number of plastic pikes are parading like sentries across the channel, driven by a continuous conveyor belt. If driven at realistic speeds, these objects will generate near-field displacements every bit as large as the vibrators you are thinking of, and they have the additional advantage of stimulating the lateral line of the fish in just the right way to evoke inborn or learned predator-escape responses. How big this last factor is remains to be measured, of course. The power requirements and overall cost of this set-up would be quite minimal; in fact, it could be driven directly by a water wheel operated by the current in the channel.

MR. VANDERWALKER: As far as a near field effect is concerned, I want to emphasize that all the reactions of the fish that I observed occurred within the near field.

Fish do not usually swim downstream, they face upstream and let the current carry them, and it's very simple for them to avoid an object by increasing their swimming speed and simply turning away at an angle.

On the pressure measurements, I know that our measurements were inadequate in that we were only able to measure pressure. I would be very encouraged if anyone here would be able to tell me how I can measure the directional movement of the water in the near field because this is what I'd like to be working with.

DR. SHAW: The fundamental contribution of this paper by Mr. VanDerwalker is that he is one of the first, among the fishery biologists, to obtain from fish an avoidance response to low frequency sound. However, from the paper it is not clear if the response is to pressure waves, low frequency sounds, or related phenomenon, such as water displacements or resonance from the tank walls.

A review of the problem of fish guiding shows that it has been a serious problem among fishery biologists since the construction of hydro-electric dams on the Northwest coast of the United States. There have been a number of approaches to the problem and the need is of obvious importance, since 20 to 60 per cent of migrating juvenile fish, those migrating from the lakes and rivers into the sea, are destroyed when they must pass the entrapments inadvertently produced by the power plants. The problem has been approached several ways, either by utilizing the sensory capacities of the animals, to redirect ("guide") them, or by creating a physical barrier to deflect them. Brett, in a comprehensive review a number of years ago, pointed out that guiding is often applied to several techniques, namely attracting the fish to a particular object, inducing fish to orient in a D.C. electrical field, or frightening fish away from a damaging turbine or spillway. Actually, what is frequently involved in the attracting phenomena is approach of the fish to a stimulus of low intensity. In fright situations the animal is withdrawing from a stimulus of high intensity. Often, in the latter case the behavior of the animal, once it withdraws, is generally random and "helter-skelter". This *sometimes* can be utilized in diverting the fish from deadly objects. In the experiments presented by Mr. VanDerwalker therefore, guiding is an "escape reaction"—actually, it is a withdrawal from an apparently high intensity stimulus. In previous work two other authors working with sound frequencies, ranging from 60 Hz to 70 kHz, showed that these frequencies produced only a "start" effect, particularly in sounds of lower frequency, whereas there was no observable response to sounds above 15,000 Hz. The experiments were carried out in an open field in contrast to the more restricted test conditions of Mr. VanDerwalker's experiments. Those authors were unable to find a way in which the fish could be redirected into a bypass. Through the utilization of other sensory inputs, other methods have been tested to guide fish. These methods had to be economically feasible and technically possible. Some of the methods and their results are given below. A light source, such as a light beam or light of various intensities, gave little if any deflection of fish into a bypass (by deflection, I mean Brett's deflection of 75 per cent which is considered to be a good result). Fish entered the light field, remained there temporarily and then continued on their way. Amber or blue light has no noticeable effect but a curtain of air-bubbles with reflecting light proved to be a successful deflector—unfortunately, technically difficult. Sound was effective when light was on but did not seem to affect behaviour when the fish were in darkness. The time of darkness is when most of the migration takes place.

Odor was also tested, skin rinses of humans, and formalin, but again there was no appreciable effect. Bursts of methylene blue dye during daylight was fairly effective in deflecting the fish but only at the instant of burst. Here again is another example of a stimulus that causes, because of its high intensity, a withdrawal of the animal, but the fish quickly became adjusted and evidently no longer responded with avoidance behavior. One of the more effective techniques has been that of hanging chains at intervals of two or more inches. The physical presence was not as critical as their light reflecting properties, and fish tended to avoid the light reflections. Many of the stimuli presented to the fish have the common property of high intensity levels thereby causing a withdrawal of the fish. Actually the ideal situation would be the use of a stimulus of low intensity which would attract the fish and once the fish have approached the stimulus, they would remain oriented to the stimulus until they were well out of the area of danger. An effective method that employs this principle is a moving curtain of cables. The fish tend to take a fix on the moving curtain and are effectively guided – without any alarm reaction. My own researches have indicated that this is a workable idea, since in a classic optomotor response, fish orient to a moving field of black and white vertical stripes. The fish move at the same speed as the moving stripes and move constantly in the same direction as the stripes.

Thus, in fish guiding a number of ways have been tried. The final question remains, whether or not, in the problems of fish guiding, sound is indeed the best technique. It may be the best technique in terms of technical efficiency and cost, but in terms of truly guiding the animal without causing an intense reaction on the part of the animal, it may not be as effective as a visual stimulus.

MR. VANDERWALKER: We've tried lots of methods, including air bubbles, electricity, and we're not as optimistic as Dr. Brett. In order to maintain the present population levels, we're going to have to save 90 – 95 per cent of the fish.

The reason we're trying to use sound is because the other methods are extremely costly to build and maintain. Physical barriers, such as screens, which are commonly used now, cost a tremendous amount of money, and we thought that if sound were successful, we might be able to build something that was less expensive.

DR. MACKAY: In the second part of your experiments, did you simply switch in a sound source, or did you raise it gradually? Was this a startle reaction or an avoidance reaction?

It seems to me that there's a very interesting aspect to the experiments of this type, namely which way would a fish take off?

In an analogous situation, it's not interesting that the human eye focuses, but how it knows in which direction to get into focus that's of interest. Similarly with the ear. If a fish is suddenly immersed in a sound source, how does it know which way to go to go to a region of lower intensity? I think this is truly of interest. Is there a gradient of something along the fish that it is able to sense?

MR. VANDERWALKER: During our study we switched the amplifier in directly; however, during our preliminary studies we tried turning up the volume manually and found little difference between this reaction and the reaction to the sound when the amplifier was switched on to full power.

MR. FITZGERALD: It seemed to me you were talking about a barrier, not guiding the fish. Did I hear you right you said you had a source level of 160 dB?

MR. VANDERWALKER: Our maximum recorded pressure was 155 dB re 0.0002 dynes/cm^2.

MR. FITZGERALD: Did you observe any cavitation?

MR. VANDERWALKER: Not during the experiments we conducted, but in preliminary tests of the tank when we were practically shaking the entire area we did.

MR. FITZGERALD: At the source?

MR. VANDERWALKER: At the source.

MR. FITZGERALD: Have you ever tried setting up a cavitation barrier?

These forces on the fish would be quite terrific and they might be quite effective, and you can focus this.

MR. VANDERWALKER: No. Our experience in cavitation has been confined to its occurrence in turbines. There is evidence that this type of cavitation is harmful to fish.

DR. VAN BERGEIJK: Why didn't you use air screen? It's very simple to develop. A screen of air bubbles.

MR. VANDERWALKER: I've done quite a bit of testing with the air screen. I was able to guide 95 per cent of the fish during the day time, but at night the fish could not be guided. This indicates the response was a visual one and not a response to the sound waves associated with the air bubble screen.