# EVALUATION OF LOW AND HIGH FREQUENCY SOUND FOR ENHANCING FISH SCREENING FACILITIES TO PROTECT OUTMIGRATING SALMONIDS

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# Preface

The need to provide passage and protective screens at irrigation diversions has always been a necessary part of the Columbia River Basin Fish and Wildlife Program (NPPC 1984, 1987, 1994). From 1985 through 1990, fish protection facilities in large irrigation diversions throughout the Columbia Basin, especially in the Yakima Basin, were updated. After 1990, fish protection efforts turned to installation of new facilities on unscreened diversions and to repair and upgrade of older facilities.

The screening program also includes funds to monitor and evaluate the facilities. The screen evaluations indicate they are an effective means for protecting juvenile fish larger than 40 mm in length. As state and federal agencies change screening criteria to protect smaller fish (e.g., bull trout fry), the physical barrier may not always be effective. Screen mesh small enough to protect fish may be vulnerable to frequent plugging. Gap tolerances on side and bottom seals may be difficult to install and maintain. Physical barrier screens can be enhanced with behavioral barriers that cause fish to avoid a hazard. Behavioral barriers may consist of sound generator, strobe lights, bubble curtains, or electrical barriers. State of Oregon House Bill 3112 states that "*Standards and criteria shall address the overall level of protection necessary at a given water diversion and shall not favor one technology or technique over another*." Additionally, it goes on to say, "*Screening device means a fish screen or behavior barrier.*" Other Northwest states, in particular Washington, have taken a comprehensive program to install barriers at all unscreened diversions by 1999. Protecting all fish at all water withdrawals will probably require both physical and behavioral barriers.

The purpose of this study is to evaluate the effectiveness of using an underwater sound-generator as a behavioral barrier for possible use at fish diversion facilities. This study did not include engineering and economic evaluations needed to produce, deploy or install sound equipment at existing or planned fish screening facilities. The focus of this study is to determine if fish, specifically juvenile salmonids, can be guided by sound.

# Acknowledgments

The success of this project depended on the involvement and cooperation of many people. The project was managed by Jodi Stroklund and Tom Clune of the Bonneville Power Administration (BPA). Jeff Condiotty and Roger Campana from Simrad Inc. and Paul Novakovik from EESCO Inc. were of great help in the leasing of sound projectors. Gene Ploskey of the Waterways Experiment Station provided assistance in conducting infrasound testing and sound field mapping in 1997. We would also like to thank Sue Blanton, Eric Gaedeke, Fenton Khan, Jeff Marco, and Robin Sternberg for their assistance in conducting the tests and analysis of the tapes.

# Abstract

Fish screening facilities are used to prevent fish from being entrained in pumps or trapped in irrigation canals. Screens have diminished utility when they are needed to protect fish that are less than 40 mm long. Small mesh screens are easily clogged and tolerances for sealing the sides and bottoms of screen civil works are difficult to construct and maintain. If fish screens could be enhanced with a behavioral barrier component, screen mesh and seals may not need to be so small. We subjected 30-70 mm rainbow trout (*Oncorhyynchus mykiss*) and chinook salmon (*O. tshawytsha*) fry to low frequency (7-14 Hz) and higher frequency (150, 180, and 200 Hz) sound fields to assess the possibility of using underwater sound as a behavioral barrier for enhancing fish screening facilities. Both species responded to infrasound by an initial startle response followed by a flight path away from the source and to deeper water. These observations indicate that juvenile salmonids, as small as 30 mm long, have infrasound detection capability when the particle motion exceeds $10^{-2}m/s^2$ at a frequency of 7-10 Hz. Additionally, it may be possible to predict the direction of response for juvenile salmonids. We observed a startle response in wild chinook salmon when exposed to high-intensity (162 dB //*m*Pa), 150-Hz pure tone sound. No observable effects were noted on hatchery chinook salmon or rainbow trout fry when exposed to 150, 180, or 200 Hz high-intensity sound.

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# Introduction

Knudsen et al. (1992, 1994, 1996) showed that juvenile Atlantic (Salmo sp.) and Pacific salmon (Oncorhynchus sp.) pre-smolt and smolt exhibited avoidance responses to the local flow component of infrasound within the near field of volume displacement infrasound sources. Knudsen found that smolt (>100 mm) responded when the local flow acceleration was greater than $10^{-2}$ m/s$^2$ at a frequency of 10 Hz with an innate avoidance response. The experiments conducted by Knudsen et al. (1992, 1994, 1996) and Taft et al. (1995) followed from several decades of experimentation to identify sounds that would elicit a response from salmonids (Carlson 1994). These experiments were remarkably unsuccessful until reanalysis of the hearing ability of salmonids identified the components of underwater sound fields that salmonids are able to detect. It was found that the majority of energy produced by swimming fish is below 20 Hz and the otolith organs of the inner ear are responsible for the detection of accelerated flow field (Kalmijn 1988). The detection of low-frequency sound fields are used by many species of fish to locate predators and prey, obstacle avoidance and schooling (Popper and Platt 1993).

Almost all of the sound response testing with salmonids has been with larger juveniles because of the focus on downstream migrating smolts. However, there is also interest in the response of earlier life stages because of the need to improve fish protection at irrigation facilities where fry are present and may be entrained. In general, the fish at most risk in these situations are sub-yearlings less than 60 mm in length.

There are many reasons that suggest the response of sub-yearlings might be different from that of larger juvenile salmonids. Obviously, smaller fish have less swimming ability and, potentially, more immature sensory systems, both attributes that would influence their ability to detect and react to infrasound. For example, recent morphological research still underway has shown that younger Pacific salmonids have fewer inner-ear hair cells. Thus, for the youngest stages, such as swim up fry, the otoliths, located in the inner-ear end organs, have not fully calcified (Arthur N. Popper, Ph.D, University of Maryland, College Park, Maryland personal communication).

The differences in the number of hair cells, degree of development of the inner ear between early stage juveniles and smolt, in addition to other physiological differences, raised the question of whether salmonid fry would react to infrasound in a manner similar to smolt. One question addressed by the research conducted in this study was, “Do Pacific salmon fry react to the local flow of volume displacement sources operating near 10 Hz?” Of special interest were the responses of juveniles less than 60 mm in length exposed to local flow particle acceleration values greater than $10^{-2}$ m/s$^2$.

In addition to low frequency sound fields researchers have used higher frequency sources to create a behavior barrier or to guide fish away from intakes. The majority of the success in this area has been with fish species described as hearing “specialists”(Schellart and Popper 1992) which can detect frequencies up to 2,000 Hz. Salmonids are considered hearing “generalists” and can detect sounds up to 500 or 600 Hz. We exposed salmonid fry to pure tone frequencies of 150, 180, and 200 Hz, which are well within the published hearing range of salmonids (Hawkins and Johnstone 1978).

# Methods

We placed caged fish in a large tank to test the response of juvenile salmonids to sound. A sound source was placed next to the cage with sound directed toward the cage. Using underwater video cameras, we recorded the response of the fish. Fish movement away from the sound source was interpreted as a positive response to sound.

## Tank

A steel reinforced, oval fiberglass fish tank (from Gemini Pools, Inc.), measuring 3 m wide x 7.3 m long x 1.8 m deep, was used for infrasound testing (Figure 1). This above-ground tank was positioned on a 30-cm layer of pea rock to minimize vibration. Chilled well water (~18°C) was used to aid in video recording due to its clarity. Test fish were confined to a net pen constructed of 0.16 cm nylon netting, measuring 1 m wide x 1 m deep x 2 m long, attached to a 2.54-cm-diameter PVC frame with holes drilled in the bottom and side supports to aid in submergence of the frame. The outside of the net pen was divided into 0.3-m quadrants along the bottom and on one side, with black nylon rope to measure fish movements. Quadrants were numbered 1-4, with 1 being nearest the sound device. The top portion of the tank was covered using a canvas tarp to create consistent lighting and to deter fish from concentrating in shaded areas.

**Figure 1**. Fiberglass Test Tank

## Video Equipment

The video recording system consisted of high-resolution monochrome cameras (Sony, model HVM-352) with a wide-angle lens (110°) connected to an 8-mm camcorder (Sony model CCD-FX710 Handycam Hi8). Recordings were made with Sony Hi8 tapes. Two video cameras were used to document and record fish movement. One camera was placed in the water to view back-and-forth movement along with vertical distribution. The second camera was positioned at the water surface to view horizontal movement. Video cameras operated continuously during each test series. External monitors were also used to view fish reaction while recording. Video recorders, monitors, and sound controller units were housed in a portable trailer near the tank.

## Low-Frequency Sound Sources

We used two low-frequency sound sources for these tests. Both were volume displacement source (VDS) sound generators. One was developed by Kongsberg Simrad (Simrad) and the other by Energy Engineering Services Company (EESCO).

**Simrad VDS -** A high particle displacement, local flow infrasound field was generated in the test tank using a VDS with a piston diameter of 10 cm and a displacement amplitude (peak to peak) of 4.5 cm. The VDS was operated within the frequency range 10-14 Hz. Water particle acceleration was achieved via the movement of two pistons located on opposite ends of the VDS. The VDS was driven by an electric motor requiring 230-volt, three-phase power supply connected to a programmable power driver (GE AF-300). The source was positioned 1.6 m from one end of the tank and centrally positioned on cinder blocks, 1 m off the bottom (measured to center of pistons). Rubber matting was used to absorb energy released when the VDS was operating. One end of the net pen was positioned 0.8 m from the VDS (Figure 2). Two different configurations were tested initially: 1) the piston axis in line with middle of the net pen and 2) the piston axis level with the bottom of the net pen. Based on fish response, we ran all tests with the second configuration.

The local flow component of the infrasound field generated by the source was measured using a triaxial accelerometer equipped with pitch, roll, and yaw sensors, i.e., an inertial measurement unit (IMU). The IMU sensor was placed at 0.5-m intervals from the source and the source was activated. During experimental trials, it was observed that the net pen containing the test fish would move in response to the operation of the source. A question arose about whether the net pen was modifying the sound field since it was obviously moving in response to operation of the source. A series of measurements was made to measure the local flow acceleration with and without the net pen to estimate the potential effect of the netting on the sound field. The local flow acceleration was measured for two different conditions: the tank full of water and the tank half-empty. For each condition of tank water-level, measurements were made with the IMU inside the fish containment net and at the same location with the fish containment net removed from the tank. Sound pressure levels (SPLs) were determined using a Bruel & Kjaer model 8104 hydrophone with a frequency range of 0.1 Hz to 120 kHz.

**EESCO VDS** - A prototype VDS was designed and developed for initial testing during 1997. The device had a frequency response that could be adjusted from 5 to 40 Hz. The frequency used during the tests was measured at 7 Hz with an SPL of 155 dB //*m*Pa, measured at 1 m from the face of the piston. The VDS had a piston diameter of 20.3 cm and a peak-to-peak amplitude of 6.3 cm. The VDS operated on 110-volt power supply.

## High-Frequency Source

An EESCO Model 215 underwater transducer, with an operating range of 100 Hz to 1 kHz, was used to generate the 150-200 Hz sounds. The transducer produced an SPL at 1 m from the transducer of 162 dB //*m*Pa. An amplifier and waveform generator was used to drive the transducer. The transducer was suspended at a mid-water depth (0.7 m) near one end of the test tank. The net pen was positioned 0.8 m from the transducer. Each test group was subjected to 150-, 180-, and 200-Hz frequencies over a two-day period.

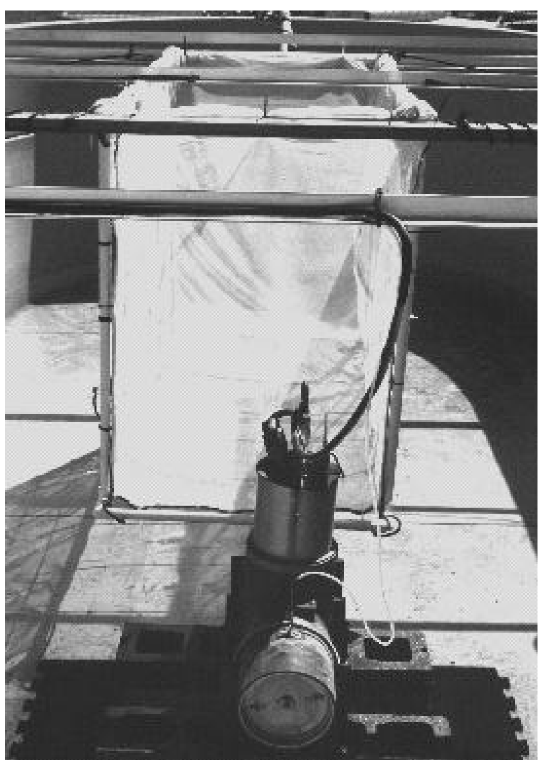


**Figure 2**. Location of the Simrad Infrasound VDS in Relation to the Net Pen

## Test Fish

Rainbow trout fry, hatchery fall chinook salmon fry, and wild fall chinook salmon fry were used during the 1996-97 tests. Hatchery fall chinook salmon fry and rainbow trout fry were raised from eggs at the hatchery facility at the Pacific Northwest National Laboratory (PNNL). Wild fall chinook salmon fry were seined from the Columbia River and held at the PNNL facility before testing. Table 1 describes the test fish and sizes for tests completed in 1996-97. All fish were acclimated to chilled well water (14°C) before being transferred to the test tank. The test fish used were similar in both evaluations and were slightly larger during the 1997 evaluation. Due to the delay in obtaining the EESCO VDS during the spring of 1997, testing was conducted later than anticipated. This delay impacted our ability to collect wild chinook salmon fry from the Columbia River. As a result of the increased holding periods, several wild chinook had visible signs of columnaris disease. We did not use these fish during the tests.

**Table 1**. Species and Average Length of Test Fish Used During Sound Testing 1996-1997

| Test Fish | Infrasound 1996 | Infrasound 1997 | High Frequency 1997 |
|---|---|---|---|
| Wild fall chinook salmon fry | 53 mm | 73 mm | 41 mm |
| Hatchery fall chinook salmon fry | 62 mm | 58 mm | 51 mm |
| Rainbow trout fry | 38 mm | 51 mm | 30 mm |

## Experimental Procedure

A total of 20 fish were acclimated in the net pen for a duration of 2 hours or more before testing. All tests were conducted during daylight hours and each test group was recorded for the entire test interval. After completion of tests, fish were dip-netted from the pen and measured. For the low-frequency tests, the VDS was activated for an average of 10-15 sec for each test with a 5-10 minute interval between tests. The ramping-up period, or time required for the pistons to achieve full operation, varied from 5 to 15 sec depending on the VDS and number of tests run. Based on previous research, a total of 15 “sound on” (reaction) tests were used as a target for each test group. For the high-frequency tests, a randomized sampling protocol was used for each test group. The test protocol involved a random selection of 10 stimuli during a 1-hour test. The sound was activated for a short period, usually no more than 20 sec per stimulus. The frequency (150, 180, 200 Hz) and specific waveform (sine or square) were also randomly chosen for each test.  For each test group, we evaluated the response by measurement of gross movement by the center of the group (school of fish) during the 15-sec sound activation.  Three categories of responses were determined during each test.  These included a slight (movement of 0.15-0.3 m), moderate (movement 0.3-0.6 m), or strong response (movement of 0.6 m or more) down or away from the transducer or VDS.

# Results

## Low Frequency (Simrad VDS)

The tests suggested that juvenile salmonids (40 - 60 mm in length) have the capability to detect low-frequency, high particle acceleration sound fields and react by eliciting a startle and avoidance response. Although these tests were conducted in a static environment, the results indicated chinook salmon and rainbow trout fry have an innate avoidance response to accelerated particle velocity greater than $10^{-2}$ $m/s^2$. Wild chinook salmon groups had the highest avoidance response at 90% for the first five tests combined. Combined response for hatchery chinook salmon and rainbow trout groups exhibited a strong response 70% of the first five sound on tests. In all test groups, there was a strong flight path down and to deeper water, then away from the VDS. Average time for habituation to infrasound occurred after the 7th to 10th test for chinook salmon, but no pattern was observed for rainbow trout (Table 2). For all test groups, the initial response to the operating VDS was rapid movement towards the bottom of the pen and then away from the source. Both wild and hatchery chinook salmon fry were attracted to the area near VDS after repeated exposures. Whether this behavior is due to attraction or habituation could not be determined from the tests. Individual fish also responded to the sound of motor noise before the pistons engaged by moving away from the VDS. This was particularly evident in the later stages of the test series.

**Table 2**. Summary of Infrasound Tests (1996) Using the Simrad VDS (Group movement values represent a combination of all test replicates)

| | | | Percent Group Movement During First 5 Sound-On Tests | | | |
|---|---|---|---|---|---|---|
| | Number of Test Replicates | Frequency, Hz | Slight, 0.15-0.30 m | Moderate, 0.30-0.60 m | Strong, 0.6 m or more | Number of Tests Before Habituation |
| Wild chinook | 4 | 10-14 | 0 | 10 | 90 | 9-10 |
| Hatchery chinook | 4 | 10-14 | 10 | 20 | 70 | 7-8 |
| Rainbow trout | 4 | 10-14 | 20 | 10 | 70 | none |

During initial testing, with the bottom of the net pen below the VDS, the fish responded to the infrasound by moving down vertically below the VDS. It is postulated that the fish are avoiding the sound field by moving down to an area of the pen that they perceive to be safe. When the net pen was raised, so that the bottom was on the same plane as the VDS, the fish reaction was markedly different. While the initial movement was still down, the fish tended to move horizontally towards the rear of the net pen. This behavior indicated that the net pen was restricting the fish in their movement away from the VDS.

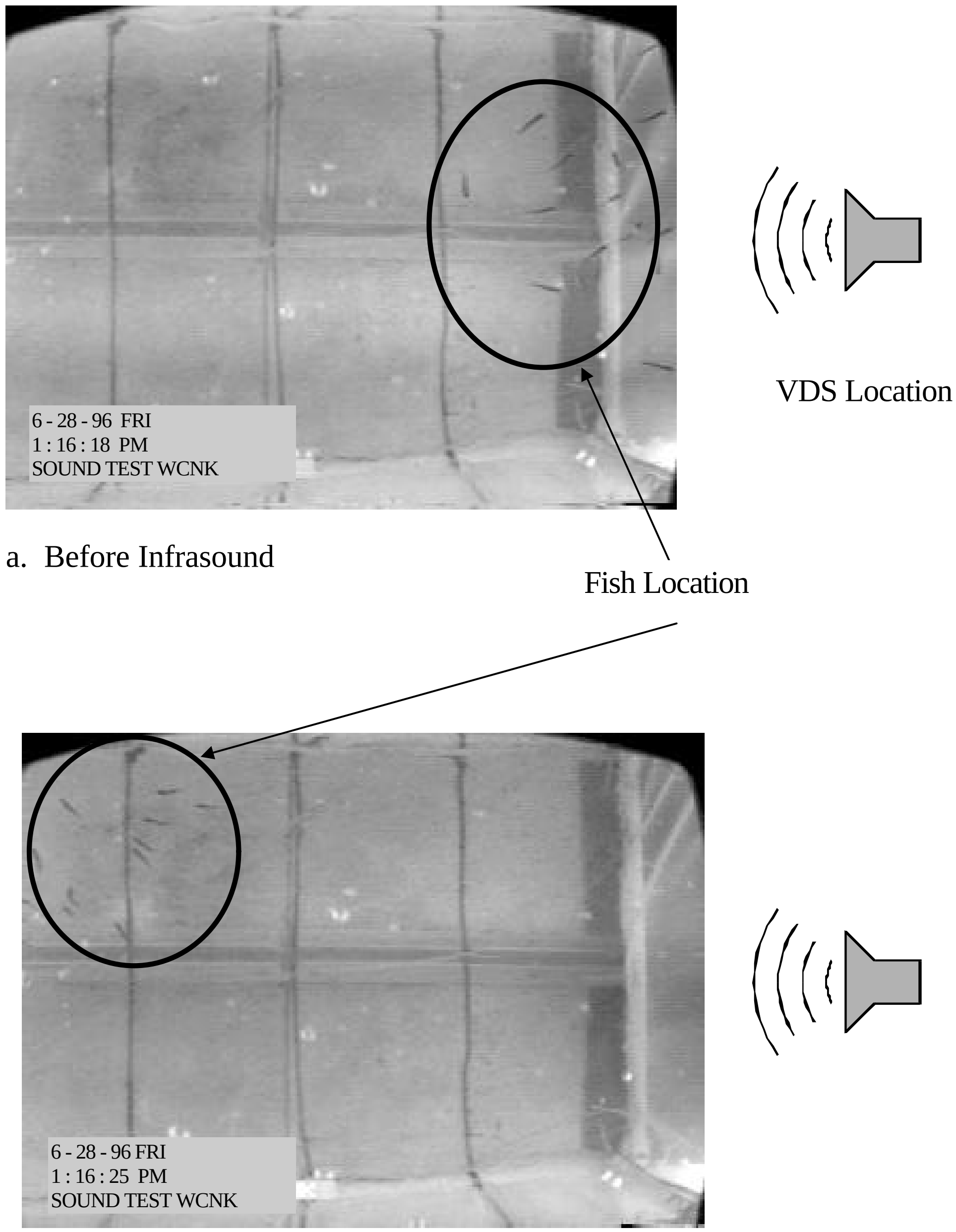
Due to the temporal increase of friction in the pistons, the interval between activation of VDS and actual piston movement became longer (up to 8 sec) in the later part of the test series. In some test groups, fewer than 15 tests were conducted due to seizure of the pistons. When this occurred, the water level in the tank was lowered and the pistons were relubricated. For all species of fish, movement was generally categorized as moderate to strong for all test groups. The specific behavior for the species tested is presented below.

## Rainbow Trout Fry (Low Frequency with Simrad VDS)

Rainbow trout tended to exhibit the least avoidance response compared to chinook salmon fry. Their behavior was characterized by a short-term, random movement startle response, followed by a deliberate movement away from the VDS. Before activation of the VDS, fish were dispersed throughout the middle portion of the net pen. When the source was activated, the group exhibited a strong avoidance response by moving away from the VDS ~0.6 m, followed by a general movement down to the bottom of the net pen. After the fourth test, a general avoidance response was observed such that fish formed a tight school and moved to the lower back corner of the net pen. In two of the four test groups, individual fish would scatter in many directions at the same time. This type of behavior has been documented as innate response to the presence of a predator and called “flash expansion” behavior (Keenleyside 1979). Generally, after the tenth test, the group remained on the bottom and back half of the net pen.

## Wild Chinook Salmon Fry (Low Frequency with Simrad VDS)

During the acclimation period, the test fish were located in the upper part of the water column in a loose school. Fish located near the VDS would form a tight school and exhibit a strong flight response (down and away), followed by an avoidance response (see Figures 3 and 4). When individual fish were located in the upper rear or center of the pen, initial response to the VDS was to move down to the center of the net pen. After the sixth through ninth tests, the




a. Before Infrasound

b. After Infrasound

**Figure 3**. Temporal Response to Infrasound by Wild Chinook Salmon Fry. A top-mounted camera looking down recorded the images shown. Image (a) shows the location of the fish near the source end of the net pen and near the surface. Image (b) shows the fish location during exposure to infrasound. Fish have moved back about 1 m and were closer to the bottom of the net pen.

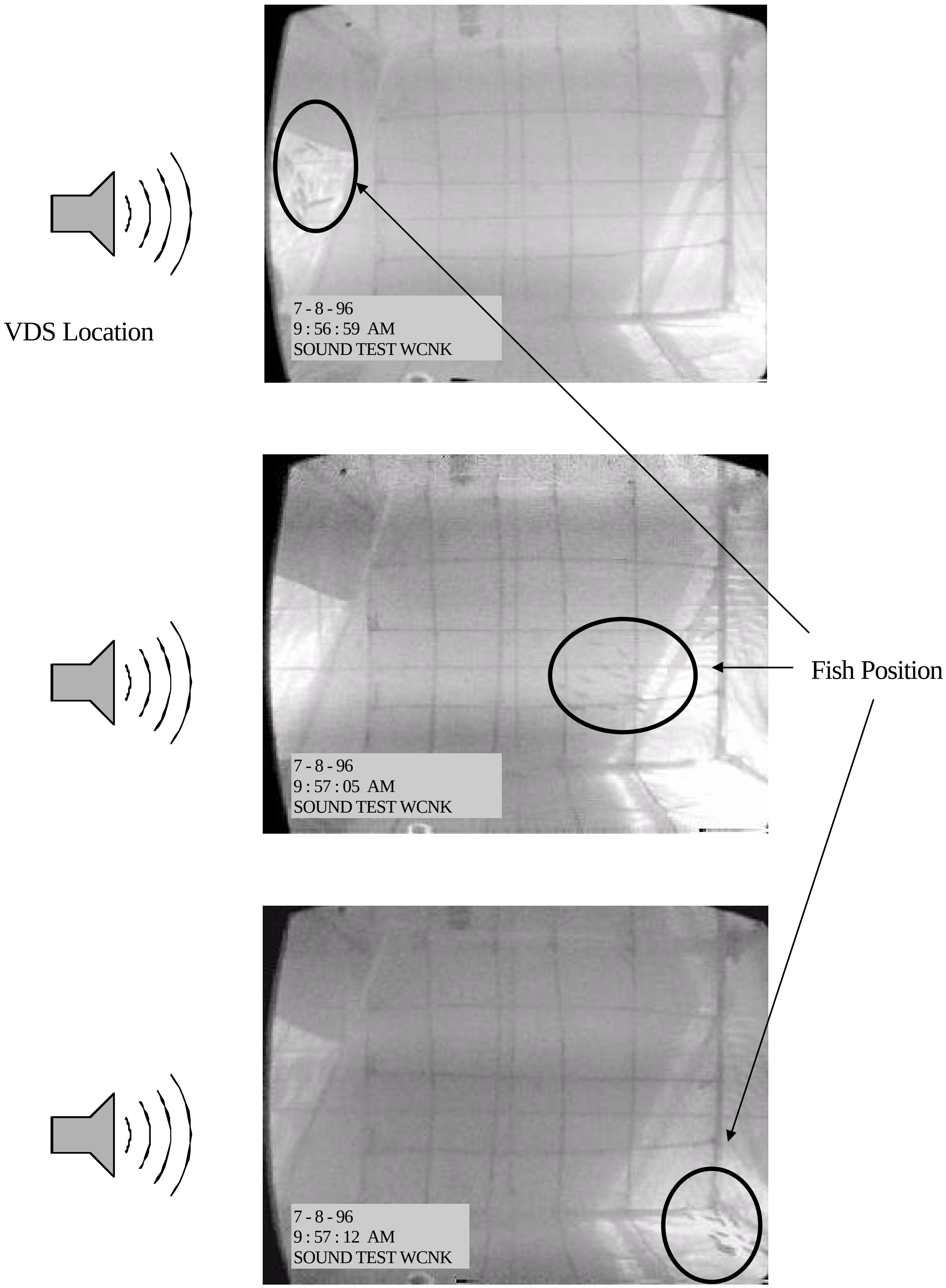



**Figure 4**. Response of Wild Chinook Salmon Fry to Infrasound. Lower images capture vertical movement of wild chinook salmon before, during, and after activation of infrasound. Initial fish behavior included a startle response followed by flight path down and away from the VDS.

group would orient towards the VDS and appeared attracted to the water displacement created by the piston movement. We speculate that this behavior occurred due to habituation and an instinct to orient towards a flow field.

## Hatchery Fall Chinook Salmon Fry (Low Frequency with Simrad VDS)

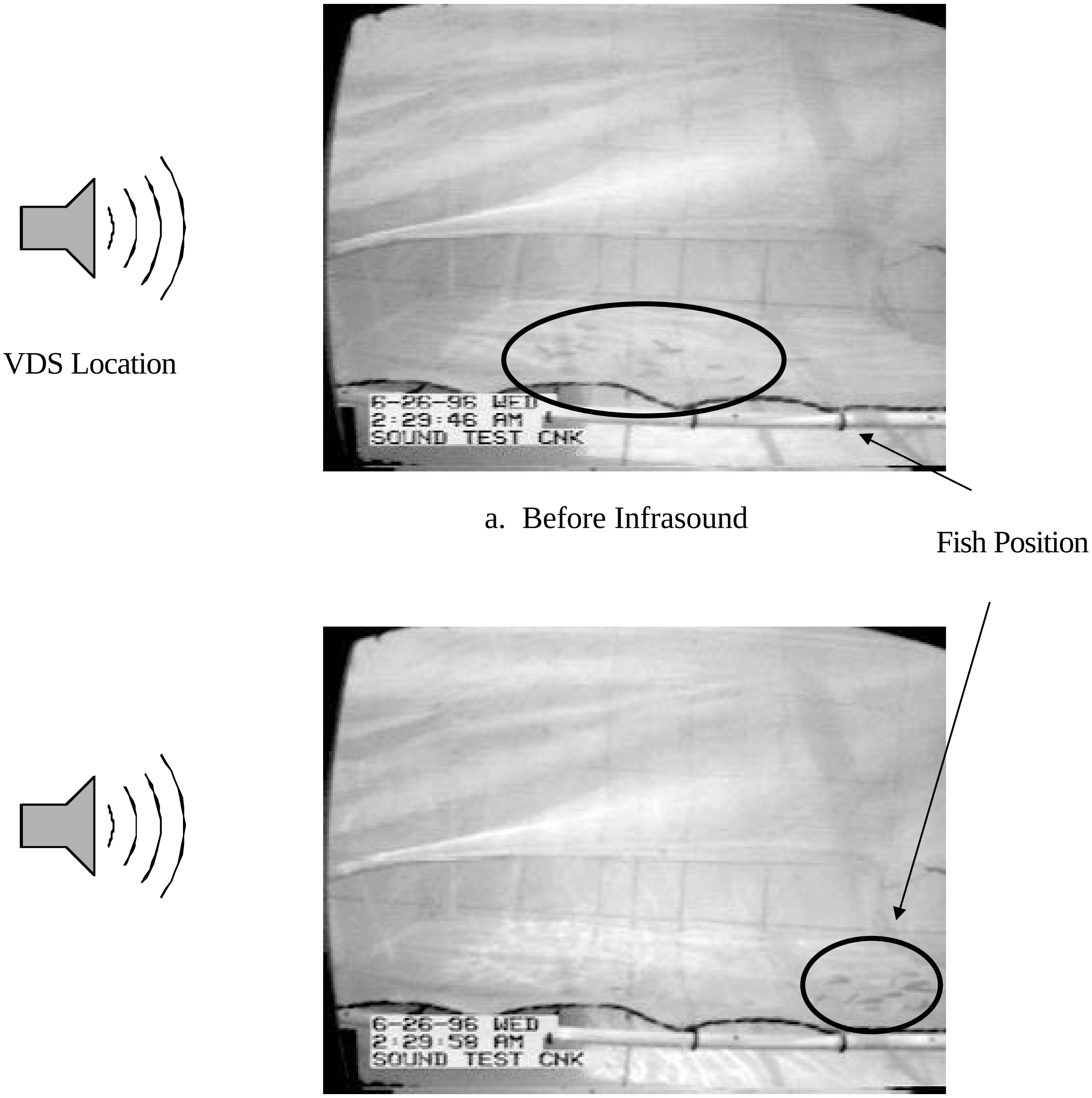
During the acclimation period, the test fish were scattered throughout the lower portion of the net pen. When the VDS was positioned above the bottom of the net pen, the group reacted by swimming down and into a corner near the source. Fish were observed schooling near the bottom of pen by the fifth test. In subsequent tests, behavior patterns included moving in an erratic manner for a distance of about 30-cm and then becoming stationary. Some fish reacted to the sound by swimming quickly to the opposite end of the pen. Habituation to the infrasound source seemed to occur by the ninth to eleventh test. We also noted that fish behavior was different when the bottom of the net pen was raised to the same level as the VDS piston. Fish were loosely aggregated prior to activation, but at VDS activation the fish would form a tight school and slowly move away from the source to an area about 0.8 m from their initial location (Figure 5). The fish also responded to the infrasound motor noise by moving away from the VDS.

## Low-Frequency (EESCO VDS)

The initial response of the two species tested was not as conclusive as with the Simrad VDS. The test procedure and recording of fish behavior responses were conducted in a similar fashion for both test series. The results indicated that fish responded by moving in the slight to moderate range when exposed to low-frequency sound (Table 3). Wild chinook fry were most likely to be deterred by the onset of the VDS with 35% of the four groups tested moving away from the source 0.3 – 0.6 m during the first five sound on tests. Habituation to the VDS was observed after about six tests. Due to the slight responses in hatchery chinook and rainbow trout fry, habituation was not apparent.

## High-Frequency Tests

Results from the high-frequency tests were not as profound and consistent as the low-frequency tests. Most test groups exposed to a pure tone frequency of 150, 180, and 200 Hz at an SPL of 162 dB //mPa at 1 m, for duration of approximately 15 seconds, showed a wide range of behavior response. Table 4 summarizes the results from the experiments conducted during 1997.




a. Before Infrasound

b. After Infrasound

**Figure 5**. Before and After Response of Hatchery Chinook Salmon Fry to Infrasound. In image (a), the fish are relatively dispersed near the bottom of the pen. During infrasound (b), the fish oriented away from sound and moved to back end of pen forming a tight school. Fish location is denoted by circle.

**Table 3**. Summary of Infrasound Tests (1997) Using the EESCO VDS (Group movement values represent a combination of all tests replicates.)

| | Number of Test Replicates | Frequency, Hz | Percent Group Movement During First 5 Sound-On Tests: Slight, 0.15-0.30 m | Moderate, 0.30-0.60 m | Strong, 0.6 m or more | Number of Tests Before Habituation |
|---|---|---|---|---|---|---|
| Wild chinook | 4 | 7-9 | 55 | 35 | 10 | 6-10 |
| Hatchery chinook | 6 | 7-9 | 93 | 7 | 0 | none |
| Rainbow trout | 3 | 7-9 | 92 | 8 | 0 | none |

**Table 4**. High-Frequency 150-, 180-, 200-Hz Sound and the Effect on Juvenile Salmonids (Positive response indicates movement of group 0.6 m or more away from transducer. Number of random sounds on tests = 10)

| Test Fish | Pulse Interval, sec | Frequency, Hz: 150 | 180 | 200 |
|---|---|---|---|---|
| | | Percentage of Tests in Which Group Exhibited Positive Response | | |
| Wild chinook | | | | |
| Group 1 | 15 | 30 | 60 | 20 |
| Group 2 | 15 | 80 | 30 | 20 |
| Group 3 | 15 | 50 | 30 | 20 |
| Group 4 | 15 | 30 | 0 | 30 |
| Average | | 47.5 | 30.0 | 22.5 |
| Hatchery chinook | | | | |
| Group 1 | 15 | 10 | 20 | 10 |
| Group 2 | 15 | 0 | 0 | 0 |
| Average | | 5.0 | 10.0 | 5.0 |
| Rainbow trout | | | | |
| Group 1 | 15 | 50 | 40 | 20 |
| Group 2 | 15 | 0 | 20 | 20 |
| Average | | 25.0 | 30.0 | 20.0 |

We did not observe any definitive behavioral responses in the rainbow trout or the hatchery chinook salmon fry. However, we did observe a behavioral response for wild chinook salmon fry in two of the four groups tested. The strongest behavior response occurred with wild chinook salmon fry at 150 Hz, followed by those at 180 and 200 Hz. The specific waveform (sine and square) did not elicit any visual differences in test group behavior. The behavior response of wild chinook salmon to high-frequency sound differed from the low-frequency responses in that the groups startle response was less evident and the avoidance response was slower to occur.

## Sound Field Mapping (Simrad VDS)

Measurements of the local flow acceleration were inconclusive, with or without the net pen to estimate the potential effect of the netting on the sound field. At short range, the net appeared to reduce local flow acceleration, while at longer range the local flow acceleration increased. More measurements under conditions where the sound field is not influenced by boundaries will be required to determine if the net material affects the near field of low-frequency sources. For the purposes of this study, the data suggest that the net reduced the level of local flow acceleration inside the net, the situation indicated by measurements made nearer the VDS. At longer range, it is likely the shallow VDS submergence and nearness of the tank to the sound waves resulted in multipathing or other effects that modulated the sound field. This phenomenon likely affected measurements of the net effect on local flow accelerations. Nonetheless, the measurements are representative of the local flow accelerations that the fish were exposed to during trials. Even with the netting in place, there was a shallow gradient in local flow acceleration in which acceleration values decreased with increasing distance from the source. In all cases, even for the maximum range at which a measurement was made (4.2 m), the local flow acceleration exceeded the minimum required for fish reactance ($10^{-2}$ m/s$^2$). All of the local flow measurements were significantly above the background noise level in the tank, which was measured to be 6.948E-4 m/s$^2$ (Table 5).

The accelerations measured in the test tank were compared with measurements made under other conditions using the same VDS and IMU. The other conditions were a test tank with dimensions of 3 m x 3 m x 3 m, located at the Simrad production facility in Seattle, Washington, and measurements made under open-field conditions in the Snake River at Hood Park, just east of Pasco, Washington. These measurements were made as an element of another study to characterize the VDS (Carlson and Campana 1996). Figure 6 presents the results of measurements made to characterize the VDS and also includes a curve fit to the acceleration data for the PNNL tank with the fish containment net removed from the tank. The figure also shows curves for local flow acceleration based on the theoretical dipole local flow equations presented by Kalmijn (1988).

**Table 5**. Horizontal Component of Particle Acceleration in Test Tank for Simrad VDS

| | Distance: VDS to accelerometer, m | Acceleration in $m/s^2$ | Azimuth Degrees | Frequency, Hz | Bandwidth, Hz |
|---|---|---|---|---|---|
| Background noise | 0.3 | 0.0069 | 14 | 10.3 | 0.3 |
| Test 1 | 0.7 | 0.20 | 62 | 13.4 | 0.1 |
| Test 2 | 0.7 | 0.15 | 62 | 13.1 | 0.4 |
| Test 3 | 1.1 | 0.03 | 13 | 13.3 | 0.1 |
| Test 4 | 1.1 | 0.15 | 32 | 13.4 | 0.3 |
| Test 5 | 1.9 | 0.17 | 18 | 13.0 | 0.1 |
| Test 6 | 4.2 | 0.03 | 8 | 12.6 | 0.2 |
| Test 7 | 4.2 | 0.06 | 8 | 13.3 | 0.1 |

Review of Figure 6 shows that the local flow accelerations measured in the Simrad test tank and the PNNL tank were quite similar. In addition, both of the sets of tank data were below that for the open field measurements. The local flow dipole equations show that local flow acceleration should decrease as the cube of distance ($R^{-3.0}$) from the source. Clearly, boundaries modify the rate of decrease of local flow acceleration. The tank data sets show the smallest rate of decrease ($\approx R^{-1}$) with range. The open field rate of decrease with range ($R^{-2.6}$) was closer to that expected from theory. However, the value of local flow acceleration at all ranges was highest for the open field measurements. The tank measurements were lower than theoretical at ranges less than approximately 0.5 m, were higher for greater ranges, and, in the case of the Simrad test tank, were approaching those for open field conditions as the range approached 2 m. It is important to note that the smaller exponent for the tank data indicates, as shown in the figure, that the local

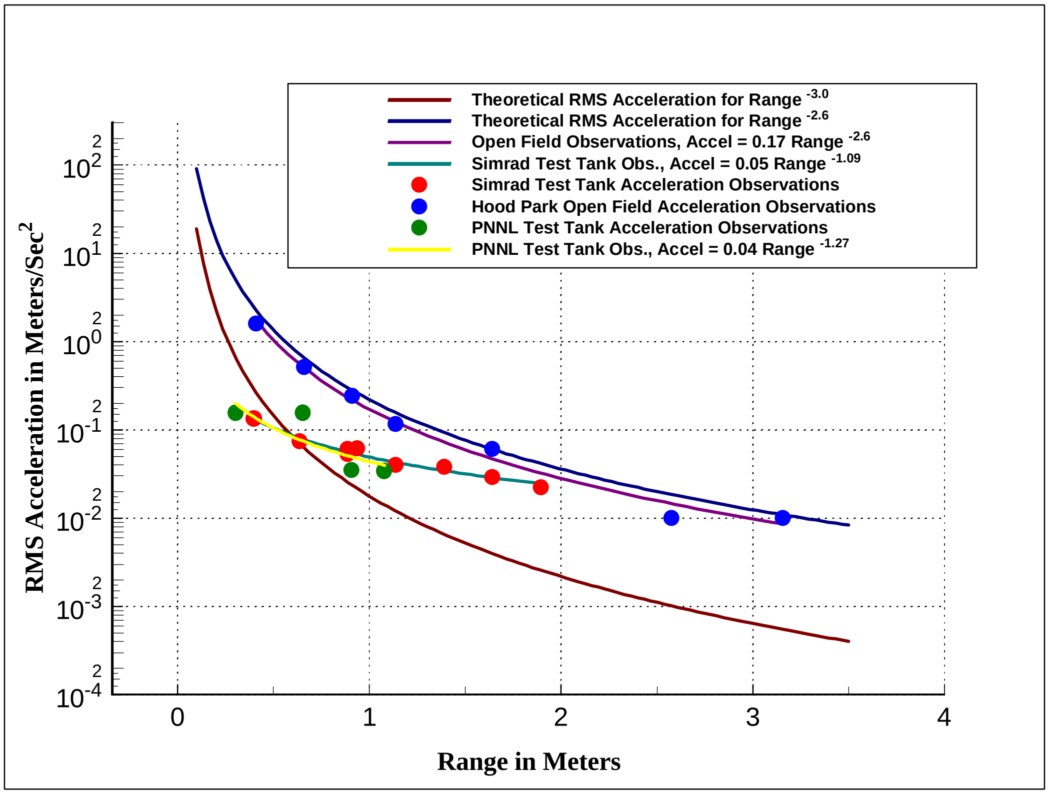



**Figure 6**. Flow Acceleration Curves Based on Theoretical and Actual Field Situations (from Carlson and Campana 1996)

flow acceleration gradient in the test tank was shallow from 0.5 m and beyond. The consequences for interpretation of fish-response data are not clear, but it is likely that the lack of a strong local flow acceleration gradient resulted in fish response that will likely differ from that observed under more open field conditions.

## Sound Field Mapping (EESCO VDS)

An extensive sound field mapping was conducted in the test tank using a calibrated accelerometer. Measurements were made at ranges of 0.5 m to 2.5 m on-axis and 1.1 to 1.85 m off-axis of the VDS. In addition, measurements were made with the accelerometer mounted on the tank wall and 15 cm away from the tank wall. Results of these measurements are presented in Table 6. All measurements were well above the minimum value required to elicit an avoidance response in salmon smolts.

**Table 6**. Horizontal Component of Particle Acceleration in Test Tank for EESCO VDS. Values Taken 10 sec After Onset of the VDS, Frequency = 7 Hz.

| Distance: VDS to accelerometer, m | Degrees off axis | Acceleration in $m/s^2$ |
|---|---|---|
| 0.5 | 0 | 0.165 |
| 1.0 | 0 | 0.175 |
| 1.1 | 25 | 0.204 |
| 1.75 | 0 | 0.170 |
| 1.85 | 22 | 0.190 |
| 2.5 | 0 | 0.188 |
| On tank wall | Na | 0.25 |
| 15 cm off wall | Na | 0.20 |
| On tank wall | Na | 0.26 |
| 15 cm off wall | Na | 0.20 |

# Discussion

Our findings that low-frequency, high particle motion was the effective at invoking flight and avoidance responses generally agree with findings from other researchers, such as Knudsen et al. (1992, 1994, 1996), who evaluated Atlantic salmon, brown trout, and juvenile chinook salmon smolts. The general behavior response of the test fish was to swim away or to an area of the test tank perceived to be safe. Test fish used in these studies ranged in size from 100 to 150 mm. We documented similar behavior with wild and hatchery chinook salmon fry as well as rainbow trout fry 30 mm in length. In related studies conducted at the Dryden Irrigation Diversion near Wenatchee, Washington, Dolat et al. (1995) found that an array of infrasound devices placed upstream of the canal intake was moderately successful at deterring 80 to 200 mm yearling salmonids from entering the irrigation canal. The study was not able to determine the effective-ness of low frequency on chinook salmon fry. McKinley and Patrick (1987) were successful at diverting sockeye salmon smolts from a fyke net opening at ranges up to 1 m using a low-frequency sound source.

In our tests, fish did habituate after repeated exposures (i.e., more than 5 to 8 tests) and, in some instances, were attracted to the area near the VDS. This behavior can be explained in part by the fact that juveniles will orient into a flow field as they would in a raceway or in the wild. Studies by Knudsen et al. (1992) suggest that chinook salmon smolts became habituated faster when the interval between stimuli was decreased. Based on these observations, it would be important to provide an avenue of escape so fish can be directed away from the sound field.

We can only speculate on why we saw such a dramatic difference in behavior responses for the low-frequency VDS. The obvious difference was the design of the units. There were some notable differences between the two devices:

- The EESCO device used a flexible outer rubber boot to encase the pistons, in contrast to the Simrad VDS in which the pistons were enclosed within a steel tube.
- The amount of time required for the piston to achieve maximum rpm was greater for the EESCO VDS.
- The operating frequency of the EESCO VDS was from 7 Hz, while the Simrad VDS ranged from 10 to 14 Hz.
- Another notable difference is that while operating the EESCO VDS, the sidewalls of the tank were acting as a separate infrasound source during the later portion of each test. An accelerometer on the wall measured 7 Hz from the oscillation. Thus, fish behavior may have been influenced by this action.

- The fact that some of the wild chinook salmon test fish were somewhat stressed during the 1997 tests could be a significant factor in the way they responded.

Results obtained from these tests suggest that low-frequency sound may be used to complement an existing physical barrier. Such an arrangement may be beneficial in protecting juvenile salmonid fry at irrigation diversions. Protecting fry using physical barriers can become very expensive and labor-intensive as criteria become more stringent. This will be particularly true as more salmonids are listed for protection under the ESA. The advantage of infrasound sources is that the effective range is rather limited; they could be utilized to create an array near the water diversion without impacting gross fish movements in the river (Figure 7). If the majority of the fish normally entrained by the canal can be directed away from the intake using a behavior barrier, screens would be more effective and the number of fish bypassed would decrease.

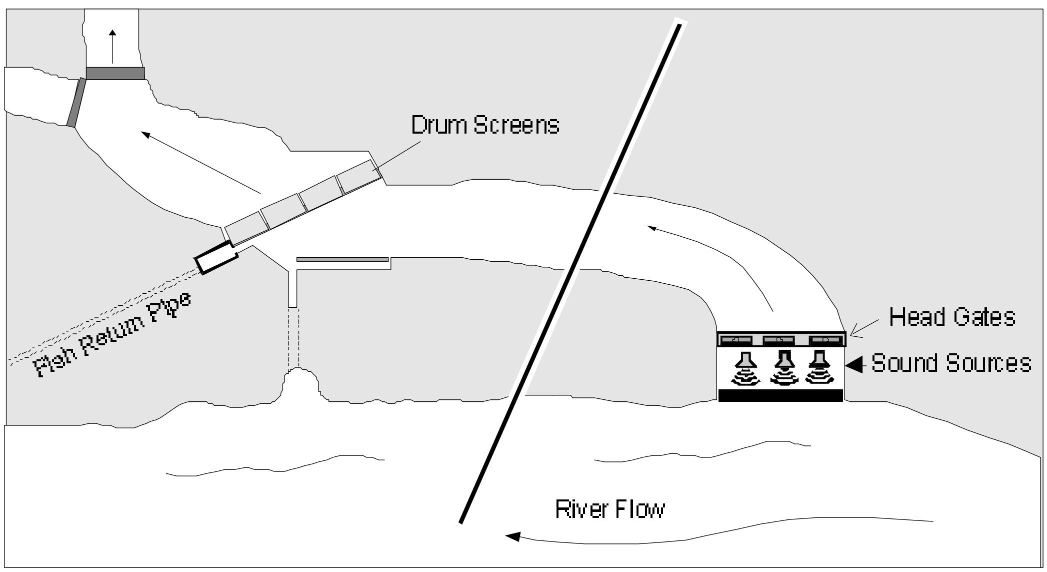



**Figure 7**. Generic Irrigation Diversion Facility with Behavior Barrier Component

Studies have shown that the upper-threshold hearing range for salmonids is 380 Hz, with the scale rising steeply above 200 Hz (Knudsen et al. 1992). Other researchers demonstrated that high frequency (150 Hz) at high intensity (4 $m/s^2$) did not cause any change in behavior (Hawkins and Johnstone 1978, Knudsen et al. 1994). Other studies (notably Loeffleman et al. 1991a,b) have reported success in diverting steelhead and chinook salmon smolts using variable frequencies from 60 to 120 Hz in a pulsed pattern. The results indicate that up to 81-94% of the juvenile salmonids were successfully diverted. It is speculated that these complex synthesized sounds may unintentionally produce low-frequency components causing the fish to exhibit an avoidance response (Knudsen et al. 1994).

Our studies demonstrated that a startle response could be elicited in the near field, particularly for wild chinook salmon fry. Why wild chinook salmon exhibited a startle response while fish raised in a hatchery did not may be explained by the fact that hatchery fish may be conditioned to similar man-made sounds within the frequency range tested. We speculate that the chinook fry were reacting to the near-field increase in SPL, which was measured at 162 dB//*m*Pa at 1 m. Studies have shown that sound-intensity level must be 70-80 dB//*m*Pa above the hearing threshold at 150 Hz to obtain a behavior response. Our test results are in agreement with Knudsen et al. (1992, 1996). The authors found no avoidance response behavior at high intensity (150 Hz) for hatchery-raised Atlantic salmon, spring chinook salmon smolts, and rainbow trout.

We believe that the use of low-frequency sound has the potential to direct juvenile salmonids away from small to medium-sized water diversions. Additional lab and field studies with salmonid fry will need to be conducted with statistical rigor in order to validate the research conducted thus far. Resource managers will decide whether sound and/or other behavioral deterrents, such as light barriers, prove most effective. In the interim, investments made in this area should prove to be beneficial for increasing the survival of migrating juvenile salmonids.

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