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Developing Acoustic Technologies for Improving Fish Passage and Protection in the Columbia River Basin: Program Rationale

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Prepared for Headquarters, U.S. Army Corps of Engineers
Bonneville Power Administration
U.S. Army Engineer District, Portland

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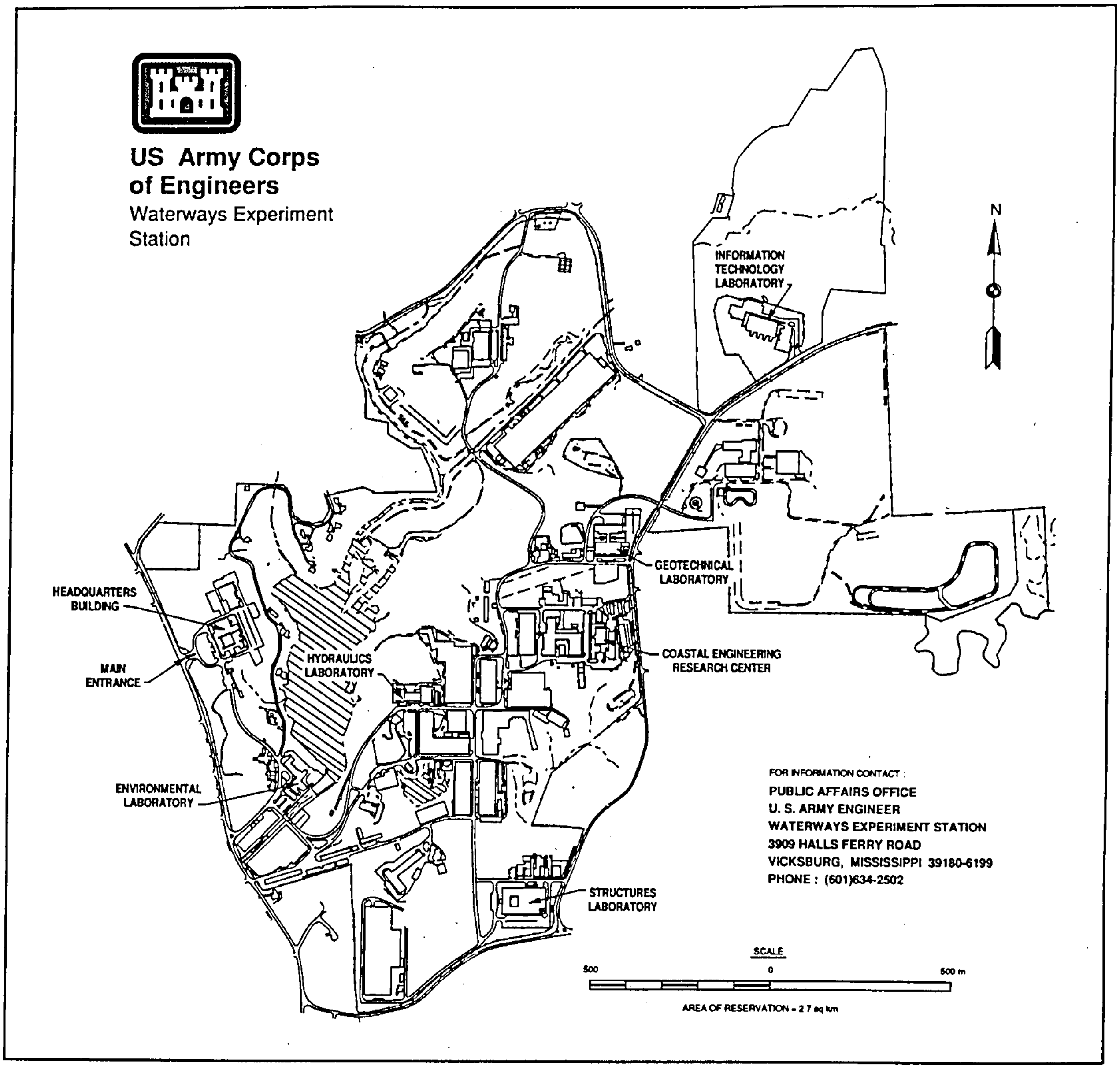

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Contents

Preface

This program rationale provides a technical framework for developing and applying acoustic technology to improve passage and protection of fishes in the Columbia River Basin. This proposal was prepared by the Environmental Laboratory (EL), Hydraulics Laboratory (HL), and Instrumentation Services Division (ISD), U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, and the Northwest Pacific Laboratories (NPL) of the Department of Energy, Richland, WA. The program rationale was prepared for the U.S. Army Engineer District, Portland, as part of the Congressionally mandated Columbia River Fish and Wildlife Program. Implementation of this program will satisfy Salmon Strategy Measure 3.7B7, "Explore promising new approaches to fish bypass technologies, including the use of sound to guide fish," and the monitoring and evaluation objectives of measure 7.2 of the Northwest Power Planning Council's Fish and Wildlife Program. Funding to prepare the rationale was provided under MIPR number E85540049 signed on 13 September 1994.

The authors of this program proposal are Dr. John M. Nestler, Water Quality and Contaminant Modeling Branch (WQCMB), Environmental Processes and Effects Division (EPED), EL; Mr. John George, Chief, Locks and Conduits Branch, HL; Dr. Tom Carlson, NPL; and Dr. Falih Ahmad, ISD. The program rationale report was prepared under the direct supervision of Dr. Mark Dortch, Chief, WQCMB, and under the general supervision of Mr. Donald L. Robey, Chief, EPED, and Dr. John W. Keeley, Director, EL. This report was also prepared under the general supervision of Mr. Glenn Pickering, Chief, Hydraulic Structures Division, HL, Mr. Frank Herrmann, Director, HL, and Mr. Pat Bonner, Chief, ISD. General supervision within the Department of Energy was provided by Mr. Patrick Poe of the Fishery Integration Branch, Bonneville Power Administration. Technical reviews by Mr. Gene Ploskey of WES and Ms. Toni Schneider of WES are appreciated. Mr. Carl Schilt of AScI, Trotters Shoals Research Facility, Calhoun Falls, SC, provided many helpful suggestions and key literature citations.

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Summary

Aquatic environments are rich in complex sound stimuli generated by wave action, internal structures of fishes, and movements of water, aquatic biota, and substrate. The capability of fishes to detect and respond to pressure and water particle motion components of sound fields is well documented. At every stage of their migration down the Columbia River system, smolts are acquiring and processing information using their sensory systems and responding in definite, and perhaps, very predictable ways. However, understanding this capability is limited by the inadequacy of standard acoustical or hydrodynamic methods to describe pressure and particle motion components of sound fields relative to fish sensory systems. There is no ambiguity, however, that fishes possess a very well-developed, highly sophisticated sensory system employed to perform those daily functions required to sustain life. It seems unreasonable to assume that fishes abandon these behaviors when they approach dams or enter intakes.

Trade-offs between efficient hydrodynamic design of bypass system components and safe, effective fish passage may require an understanding of system sound fields relative to fish sensory systems. Recently completed research at The Dalles and McNary Dam underscores the importance of understanding sound fields generated in bypass systems relative to the sensory systems of fishes. Sound fields are generated when the high-energy flow fields of intakes are partially intercepted by screen designs that differ in structural complexity. Screen-specific differences in sound fields appear to produce variations in impingement characteristics. Site-specific differences in background noise levels and turbulence resulting from trashrack design, intake configuration, intake location, and powerhouse configuration probably mediate thresholds at which fish can detect sound fields generated by the screens.

The above findings and recent advances in sound-based fish protection systems together indicate that acoustic technology has matured sufficiently, or could be expected to mature sufficiently in the near future, for application in the basin. The objective of this program rationale is to systematically develop sound-based fish protection technology to improve fish protection, passage, and health during migration through the hydrosystem. Program-level effort and support would be required to develop acoustic technology for widespread use in the Columbia River basin for the following applications.

a. Increase fish-guidance efficiency of bypass screens by modifying vertical distributions.

b. Increase fish-collection efficiency of surface-oriented collectors by modifying vertical and horizontal distributions.

c. Increase effectiveness of spilling by modifying horizontal distributions.

d. Enhance efficiency of collectors located upstream of dams by modifying vertical and horizontal distributions.

e. Repel juvenile salmonids from irrigation diversions.

f. Decrease entrainment of resident reservoir fishes during generation.

g. Attract upstream migrant adults to fish ladders and counting areas.

h. Repel adults to prevent fallback through turbines after successful upstream passage.

i. Repel squawfish from forebays and smolt bypass outfalls.

j. Attract squawfish to predator removal areas.

The goal of this program is to develop acoustic technology to complement existing and planned programs having specific fish protection, passage, and health goals. The scope of this program will include both the needs and interests of the Department of Energy and the U.S. Army Corps of Engineers. The program will be coordinated and partnered as much as the specific technical needs of the two agencies allow. Partnering opportunities with natural resource agencies, universities, Indian tribes, and the private sector will be pursued. The U.S. Army Corps of Engineers Fish Passage Development and Evaluation Program process will be used for program review and coordination.

A comprehensive, systematic research and development program merging information on sound fields, sound sensory system of fishes, and behavioral response of fishes to sound stimuli will be performed to enhance fish passage, protection, and health in the Columbia River system. This program will be systematically implemented in four phases:

- *Phase I - Existing Technology.* Evaluate existing sound-based fish-guidance and deterrence systems.

- *Phase II - Technology Inventory.* Inventory existing knowledge and technology base to identify uncertainties preventing immediate application of acoustic methods and conduct research to resolve these critical uncertainties.

- *Phase III - Systems Integration and Feasibility Evaluation.* Integrate technology components identified in Phase II into a prototype fish-guidance/deterrence system and evaluate feasibility and potential effectiveness.

- *Phase IV - Full-Scale Demonstration.* Demonstrate capability of integrated sound-based fish behavior modification systems at field scales under normal facility operating conditions for extended time periods. Depending upon research progress, demonstrations will be attempted to increase bypass screen guidance efficiency, enhance surface collection, increase spill effectiveness, and redistribute fishes at scales suitable for reduction in losses to predation.

1 Introduction

Background

Federal hydropower dams on the Columbia River Basin are located on the migration paths of valuable species and races of salmon. Many factors potentially have contributed to a steady decline in salmon stocks in the basin. Severe declines of the last two decades coincide with changes in water flow, water quality, channel shape, land-use patterns, dam retrofitting to accommodate elaborate bypass systems, and commercial and recreational fishing pressure. Recent successful applications of underwater sound to significantly improve fish protection in other regions indicate that this new technology may improve salmon passage, protection, and health within the Columbia River Basin. Other recently completed research indicates that dams and bypass systems generate distinctive, high-energy sound fields (Anderson et al. 1989, Anderson 1988) and that fishes appear to respond to sound fields generated hydrodynamically by intake screens (Nestler and Davidson 1995b).

Purpose

The results of this research will be employed by water resource developers to improve passage, protection, and health of salmon within the Columbia River Basin by reducing both direct and indirect impacts of water intakes, water resources structures, and patterns of water use. The scope of this program will include both the needs and interests of the Department of Energy (DOE) and the U.S. Army Corps of Engineers (CE). The program will be coordinated and partnered as much as the specific technical needs of the two agencies allow. Partnering opportunities with natural resource agencies, universities, Indian tribes, and the private sector will be pursued. The U.S. Army Corps of Engineers Fish Passage Development and Evaluation Program (FPDEP) process will be used for program review and coordination.

Objective

This program will develop cost-effective applications knowledge and technology for generating sound fields that stimulate predictable responses from target species and age groups of fishes. For the broadest range of potential applications, the technology must be effective from spatial scales of less than 1.0 m to hundreds of meters. It must be able to function in the turbulent, high-energy hydrodynamic environment of bypass systems and tailraces as well as in the more steady-state, laminar flow-fields upstream of dams. The sound fields can be generated by mechanical or electronic means. They can be produced hydrodynamically by water flowing over or through irregular substrates or structures. Fields can be used singly or in combination to generate stimuli that effect desired changes in fish behavior. The fields can be produced near dams, collection points, and similar locations where fishes are subject to injury or death during transit through the hydrosystem.

Specific applications envisioned by the CE and DOE include:

a. Increase fish-guidance efficiency of bypass screens by modifying vertical distributions.

b. Increase fish-collection efficiency of surface-oriented collectors by modifying vertical and horizontal distributions.

c. Increase effectiveness of spilling by modifying horizontal distributions.

d. Enhance efficiency of collectors located upstream of dams by modifying vertical and horizontal distributions.

e. Repel juvenile salmonids from irrigation diversions.

f. Decrease entrainment of resident reservoir fishes during generation.

g. Attract upstream migrant adults to fish ladders and counting areas.

h. Repel adults to prevent fallback through turbines after successful upstream passage.

i. Repel squawfish from forebays and smolt bypass outfalls.

j. Attract squawfish to predator removal zones.

2 Evaluating the State of the Art

Background

There is little doubt that aquatic environments are rich in acoustic information of value to fishes and that fishes are able to transduce and utilize that information. It is therefore surprising that there have been relatively few attempts to modify the behavior of free-ranging fishes and that of those attempts even fewer have been successful. Failures and inconsistent applications of sound to modify fish behavior exceed the documented, long-term, consistent applications of sound to guide, repel, attract, or otherwise influence the behavior of fish. An important first step for this program is to evaluate previous work and to determine the factors that have contributed to their success or failure. This step will minimize the chance of this program failing because of problems that others have encountered while working with applications of sound to modify fish behavior.

What Works and Why

Successful and reproducible applications of sound fields to redistribute fishes at the scale of operating power production facilities involve the use of electromechanically generated high-frequency (greater than 100,000 Hz) signals to repel *Alosa* spp. (Ross et al. 1993, Nestler et al. 1992). Fishes of this genus exhibit a consistent flight response, do not appear to acclimate to the signal if its frequency can be varied over time by 5 to 10 percent, and respond to the signal over significant distances (274 m). Most importantly, an adaptive value can be assigned to the signal. It may be that sounds of this frequency elicit a predator avoidance response from *Alosa* spp. The frequency of the repelling signal is in the peak energy range of the high-resolution echolocation clicks (100,000 to 200,000 Hz) used by bottle-nosed dolphins (Au 1980) and other toothed whales (Popper 1980, Woods and Evans 1980). Dolphins and porpoises are known predators of closely related fish species in marine environments and may prey on adult *Alosa* herring when these anadromous fish are at sea. The high-frequency sound must communicate information to these fishes for them to respond consistently over such long ranges.

Simple explanations of the flight response of *Alosa* spp. to high-frequency sound based on creation of internal resonances are inadequate to explain their behavior. Attempts to understand the information content of the signal as the basis of behavior separates work on *Alosa* spp. from most other investigations of acoustic fish-guidance technology.

Other researchers are looking to aquatic environments for sounds to which fish may be conditioned to respond (Knudsen, Engar, and Sand 1994, 1992). Laboratory and small-scale field experiments have shown that salmon will consistently flee from low-frequency sounds similar to those generated by approaching predators. Like the hypothesis explaining the response of *Alosa* to high-frequency sound, salmon may be conditioned to flee from a sound field associated with an active predator.

Dams and their bypass systems are known to generate high-energy sound fields thought to alter the behavior of smolts (Anderson et al. 1989, Anderson 1988). Recently completed research at The Dalles and McNary Dam underscores the importance of understanding sound fields generated in bypass systems relative to the sensory systems of fishes. That work, which involved videoimaging sections of bypass screens, indicates that high-energy turbulent features are generated on some screen designs but not others. Screen designs that generated the most turbulence had reduced fish encounter rates and reduced proportions of impingement and damage (Nestler and Davidson 1995b). Site-specific differences in background noise levels and turbulence resulting from trashrack design, intake configuration, intake location, and powerhouse configuration probably mediate thresholds at which fish can detect sound fields generated by specific screen designs.

Results obtained from bypass screen investigations are not surprising because fishes are known to respond to sound fields generated by objects in their path (Blaxter and Batty 1985). The ability of fishes to detect and avoid capture by trawls, nets, and other devices similar in their porosity to intake screens has created problems for fishermen and biologists since the first efforts to capture fishes. It is well known that, under some conditions, fishes can detect and avoid nets using their sound sensory system (hearing sense) alone since they are quite capable of such behavior under conditions when vision is impossible or disabled. Near-field pressure fields generated by vertical louvers placed at an angle to the flow are thought to be the basis of effectiveness of louvered fish-guidance systems. The above discussion strongly suggests that, to be successful, acoustic technology must integrate typical responses of fishes to: (a) engineering design of structures, intakes, and bypass screens; (b) characteristics of the hydrodynamically generated sound field; (c) elements of sound fields detected by fishes; and (d) information content of the fields to the fishes.

Sound Fields and Information Content

Successful applications of acoustic technology to improve fish protection all appear to be based on signals that occur naturally in the aquatic environment. Therefore, further development of this technology is best accomplished by gaining an understanding of basic principles governing naturally occurring underwater sound fields. Aquatic environments are rich in complex sound stimuli generated by wave action, internal structures of fishes, and movements of water, aquatic biota, and substrate. Any mechanical or hydrodynamic disturbance in aquatic environments generates complex, dynamic patterns of pressures and flows that correspond to the scale, energy level, duration, shape(s), and magnitude of the factors causing the disturbance. For example, acoustic energy generated by water flowing over a riffle or shoal is sufficiently loud that these hydrodynamic features can be detected by canoers well before they are encountered. Any organism able to detect and process the rich information content of pressure signals in aquatic environments has available to it significant information that can be used to obtain food, avoid predators, and respond to other environmental challenges.

Simplified physics of pressure signals - Monopoles and dipoles

Understanding sound field components to which fishes are responding will depend upon the ability to measure sound field components at short distances from sources with high temporal and spatial resolution. Accurate description of naturally occurring sound fields in aquatic environments using mathematical models is very difficult and probably impractical or impossible for most sound sources. As a result, much of the investigation of sound fields and the information they contain has been pursued using mathematical models for relatively simple sources, i.e., monopoles and dipoles. While these models provide insight and help assess the relative importance of the components of sound fields, they cannot be used to model complex sound fields such as are generated by the flow of water through a bypass screen in a turbine intake. Characterizing sound fields in such artificial environments requires empirical methods. This is especially true close to a sound source where relationships between sound-field components change most quickly. It may be the rapid change in certain components of the sound field that fishes rely on to gage the nearness of the source. Information obtained from a sound field when a fish is within a few body lengths of the source may be the most critical to survival. Simple mathematical models of sound fields will always have a place in research of sound fields, but may be insufficient for describing fish response to the near-field components of acoustical fields.

Sound fields in natural environments

The potential information content of naturally occurring sound fields can be visualized with a simplified narrative description of sound-field components associated with disturbances to a still medium (Schilt 1991). A complex disturbance field results when an object moves in a fluid medium (such as air or water) or when that medium itself moves in any but a laminar way. This field can be thought of as two different but not independent components. There is an elastic phenomenon that propagates in the form of a compressional wave, and there are fluid phenomena that do not (Hawkins 1993, Kalmijn 1988, 1989). The elastic component results when movement of an object in the medium or of the medium forces the components of the medium (molecules in the air or water) closer together than their structural matrix seeks for equilibrium. The components rebound and force themselves apart, overshooting the equilibrium distance and stretching the medium. This oscillation continues until the initial energy is dissipated, producing the alternating compression and rarefaction of the medium that is usually called "sound." There is no net transport of the medium in the compressional wave.

No medium is completely compressible and elastic. Very near the origin of the disturbance there will be a relatively large amount of energy that does not go into the compression and rarefaction that is the propagating wave. That energy will result in a local (not propagated) change in pressure and will produce a bulk movement in an inelastic flow that attenuates very rapidly. This is a viscous phenomenon, and its spread will be limited by viscous constraints. This aspect of the disturbance is commonly referred to as the "near field" (Harris and van Bergeijk 1962) or the "local flow" (Kalmijn 1988, 1989). The above discussion of the near-field effect is based on analysis of the sound field of dipoles or multipole sources. However, it can be expanded to include more complex sources or local disturbances that generate turbulence such as water movement over a rough substrate or movement of a complex shape (such as a fish) through a fluid medium that generate relatively slow, complex, large bulk flows that expand and slow because of friction.

All components are present throughout the disturbance field, although their relative magnitudes vary markedly with distance from the origin. The flow field attenuates more abruptly than the propagated pressure field. Most fishes can detect and process both components of sound, although many species specialize in one or the other component. For example, salmonids have relatively poor pressure to particle motion transducers compared to hearing specialist species. They are responsive only at short distances from sound sources where the particle motion component of sound fields is many times stronger than at greater distances. Other species, such as herring, have evolved specialized structures that enable them to detect sound field pressure at very long distances from a sound source (Carlson 1994).

Unfortunately, characterizations of pressure signals based on acoustical theory of wave propagation by monopoles or dipoles differ substantially from the signals generated by and radiating from complex shapes moving through water or generated by water flowing over complex substrates. Proper point source pulsating spheres are unknown in the real world, although air bubbles and to a lesser extent fish gas bladders may be roughly analogous. However, even an omnidirectional source within a fish will exhibit directivities resulting from the influence of bones and other internal structures of the fish. A swimming fish's caudal fin may nominally be a dipolar source. However, even these structures have shapes, sizes, and dampings that make them very different from textbook examples of monopoles and dipoles.

Sound fields near a source are too complex to be analyzed with mathematical models and must be characterized empirically. Until very recently, no attempt had been made under field conditions to measure sound fields at scales corresponding to the sound sensory system of fishes. Typically only a single element hydrophone sensitive only to pressure has been used. While this situation has changed to some extent with the use of laboratory instruments permitting direct measurement of particle motion, field instruments capable of measuring particle motion under typical conditions such as those within a turbine intake at scales important to fishes have not been available. Hydrophone arrays are commonly used to perform some underwater acoustic measurement tasks; however, with rare exceptions the dimensions of the arrays and the processing of the received signals have not permitted measurement of those sound field components that appear to be most useful to fishes.

Fish Hearing

Understanding the state of the art in the use of sound to attract or repel fishes requires a critical examination of the history of fish hearing investigations. Historically, the anatomy and physiology of fish hearing capability have been explored using artificially generated signals whose descriptions are based on the relatively simple, abstract physics of monopole (pulsating sphere) or dipole (a sphere or piston that vibrates in one spatial dimension) sources. Experimenters presented fishes with a selection of arbitrary signals hoping to identify signals over increments of frequency or amplitude that would elicit a response (the audiogram). While this approach has considerably expanded the understanding of the capabilities of the octavolateralis system as a receiver of simple signals, it has not produced a corresponding systematic increase in the understanding of the "acoustical ecology" of fishes, i.e., how fishes utilize and respond to the information within complex sound fields in aquatic environments. As a consequence, fish hearing is reasonably well known at the individual sensor level, but its system level functions such as processing capabilities within the central nervous system are less known.

Alternative Perspective

Review of effective examples of acoustics for fish protection indicates that using elements of naturally occurring sound fields probably holds the most promise for development of new systems. It is clear that aquatic organisms detect and extract a wide range of types of information from the pressure and water particle motion components of naturally occurring sound fields. These capabilities vary greatly among taxa and apparently are related to the evolutionary history of the species (Carlson 1994). Fishes are equipped with mechanosensory systems with which they hear (Popper and Fay 1993) and feel (Bleckman et al. 1993; Coombs, Cörner, and Münz 1989) mechanical disturbances within their environment. The "hearing" capability of fishes is best understood in human terms as a combination of hearing and touch. Even this analog is insufficient because touch is based on physical contact in humans, whereas fishes have the capability of touch sensation without the need for contact.

Observations of fish responses to complex sound fields indicate the fishes are able to utilize acoustic information for communication (Tavolga, Popper, and Fay 1981, Rogers and Cox 1988, Hawkins 1993), source localization (Chapman and Johnstone 1974, Hawkins and Sand 1977, Schuijf and Hawkins 1983), orienting (Hassan 1989), navigating (McCleave et al. 1984, Smith 1985), finding mates and courting (Gray and Winn 1961, Tavolga, Popper, and Fay 1981), schooling (Partridge 1981, Gray and Denton 1991, Denton and Gray 1992), locating prey (Montgomery 1989), and sensing predators (Kalmijn 1988). Note that many of these behaviors require information about the environment and a response within several body lengths of the fishes--that is, signal acquisition, signal processing, and response to the signal all occur in the acoustical near field. For a concise and lucid discussion of fish sensitivity to hydromechanical stimuli, see Kalmijn (1989).

The complexity of acoustic signals in the near field of the source is of major significance when evaluated relative to the capabilities of the octavolateralis system. Unlike hydrophones, fishes are not point receivers. They have two internal ears and often have gas pockets acoustically coupled to their ears that transduce and amplify pressure signals. They have geocentric orientation, inertial sense, and their mechanosensory transducers are distributed uniformly over their skins or organized into systems of linear arrays. Their sensory systems may enable them to localize sources of disturbance in two or three dimensions (Schilt and Norris, in press), describe their environment in three dimensions using the "extended touch" capability of the sound reception system, and describe the magnitude and rate of attenuation of signals as they are encountered by their sensory system. All fishes have these capabilities to some extent although some species are considerably more capable than others. These capabilities, although impressive, should be expected from active organisms living in an environment where vision is frequently rendered ineffectual by darkness or high turbidity. The interrelationships between acoustics, fluid dynamics, and fish sensory systems are best summarized by Hawkins (1993):

> Close to a sound source, however, it is not easy to draw a distinction between sound and bulk movements of the medium itself. Local turbulent and hydrodynamic effects occur which involve net motion of the medium, and neither depend upon the elasticity of the medium nor propagate at the velocity of sound...To a particular sense organ, these hydrodynamic effects may be indistinguishable from sounds.

Applying Acoustic Concepts to Real Problems - The RPSH

The relevance of sound field and fish sound sensory system concepts described earlier for improving fish passage is illustrated by results obtained from videoimaging studies of bypass systems at McNary Dam and The Dalles. Study results were integrated into the relative pressure signature hypothesis (RPSH) as a comprehensive concept of how different screen designs and deployment alternatives affect smolt behavior as they are intercepted by bypass screens. The RPSH invokes near-field sound signals as being responsible for the major differences in fish passage characteristics observed between traveling screen and bar screen designs. The RPSH provides the first comprehensive explanation of screen performance that integrates screen design, screen deployment, project operation, smolt behavior, and sound fields within the intake environment. The RPSH, combined with previous acoustical investigations (Anderson et al. 1989, Anderson 1988), strongly points to the potential use of sound signals created by the high-energy flow of water through and around the bypass system to create specific sound fields, detectable and interpretable by fish, that will improve the performance of existing fish protection systems (Nestler and Davidson 1995b).

The following explanation of the RPSH is composed of two parts. The first part explains how different screen designs or design elements producing major alterations in the turbulent characteristics of a screen affect fish behavior. The second part describes how deployment alternatives not producing major alterations of intake turbulence affect fish behavior (e.g., increases in unit load of a magnitude producing increases in velocity or a redistribution of the velocity field only but not resulting in major changes in turbulence).

Comparing screen designs

Videoimaging results suggest that bar screens and mesh screens generate substantially different pressure signatures within the intake sound field. Pressure in the following discussion is defined as pressure generated by a compressional wave, water particle motion as is generated by dipole sources, and pressure resulting from complex velocity patterns associated with turbulent water flow. First, results show water approach angles are significantly more variable within approximately 30 cm of traveling screens than they are on bar screens. Second, qualitative comparison of flow characteristics within about 30 cm of each screen design indicates that the traveling screen is characterized by variable, turbulent flows (even rollers spontaneously appear and disappear on the surface of the mesh screen), whereas the bar screen is characterized by more laminar flow conditions associated with its increased hydrodynamic efficiency. The tiedown bars, woven mesh, and structural members supporting the traveling screen interact with the larger scale turbulence present within the intake to create high-energy, smaller scale, complex and dynamic flow conditions near the screen surface. These local flow conditions near the screen surface probably generate intense pressure and acoustic fields that attenuate rapidly above the screen surface.

It is reasonable to assume that pressure and velocity fields associated with extended submerged traveling screens are more likely to be detected and avoided by approaching smolts than are bar screens, although no prototype measurements of the velocity field are available to support these inferences obtained from the imaging. However, acoustic measurements made by Anderson et al. (1989) show the existence of high-energy sound fields near dams and within the intake and bypass system, and strong inferences can be made that the sound field generated by the bypass system at Rocky Reach Dam may be responsible for its dismal fish-guidance efficiency (Anderson 1988). Conversely, structural simplicity and increased flow efficiency of the extended submerged bar screens probably produce smaller, less intense, and less fluctuating pressure and velocity fields than the mesh screen. Increased turbulence from the traveling screen probably allows approaching fishes to detect and respond to this screen design before screen impact. Conversely, smolts are more likely to strike and injure on the less detectable surface of the bar rack. This premise is supported by the increased frequency at which smolts are imaged and the increased proportion of smolts that strike the bar screen. More fishes seem to be closer to the bar screen (and hence more likely to be imaged by videocameras or strike the screen) than on the traveling screen.

The observations made on the relative differences associated with the flow fields and pressure fields can be expanded to include the rest of the hydropower intake environment by using signal-to-noise ratio concepts. The ability of a fish to detect a particular arbitrary signal is partially determined by the strength of the signal relative to the background noise, i.e., the signal-to-noise ratio. A fish may be unable to detect a signal if the strength of the signal is small relative to the magnitude of background noise.

The idea of the signal-to-noise ratio as one aspect of sensory reception also has application to the behavior of smolts near screens. The pressure environment within the intake (and perhaps the immediate approach to the trashracks) may affect the ability of a smolt to detect the presence of a screen if smolts are able to detect the presence of a screen in an intake by its pressure signature. Therefore, the acoustic and hydraulic environment in the intake also will determine the capability of a particular screen design or deployment alternative to guide smolts. Low background noise levels in a reduced turbulence environment will increase the ability of the smolt to detect and respond to (perhaps even totally avoid) the bypass screen. Thorough studies have not been made of the acoustic environment within intakes to relate characteristics of the sound field to design features. However, it seems reasonable that differences in trashrack design or orientation, bay number, powerhouse configuration, and turbine characteristics could all influence the acoustic and hydraulic environment (in a background noise context) and thus influence the guidance efficiency of a screen. Exactly the same bypass screen design may have substantially different guidance characteristics depending upon the blend of factors that together determine the background noise and turbulence characteristics of the intake. Acoustic measurements indicate substantial differences in sound pressure levels at different dams and within the intake (Anderson et al. 1989).

Comparing deployment alternatives

Contrasting near-surface flow characteristics of traveling and bar screens are greater than the differences in flow fields observed within one screen design operated under different deployment or unit loading alternatives. For example, increases in unit load or changes in screen porosity on a bar screen do not appear to alter the near-field flow characteristics as much as changes between screen designs. Effects of different deployment or operational alternatives on one screen design can probably be explored and predicted using mean water velocity and water approach angle because smolt responses appear to be linear or curvilinear to these conditions. As described for McNary Dam (Nestler and Davidson 1995a), increases in water velocity at the screen surface produce increased impingement and screen contact up to a threshold. Water approach angles that are more perpendicular to the screen surface result in increased impingement and screen contact. However, deployment or operational alternatives that produce major fluctuations in flow field near the screen surface and generate pressure anomalies that propagate from the screen surface may result in nonlinear, threshold responses by smolts similar to that observed when screen designs are compared.

New Directions

Critical review of fish hearing literature contrasted to those few examples of successful application of acoustics for fish protection indicates that new directions are required to develop operational acoustically based fish protection systems. The research elements of program activities will focus on describing and understanding naturally occurring signals in aquatic environments from the fish's perspective, i.e., to relate propagated and local flow components of sound fields to information content relative to fish sound sensory systems. If successful, this technology will allow the design, construction, and operation of "fish-friendly" hydraulic structures in the basin. This technology has the potential to alleviate many of the most significant fishery problems presently affecting Federal dams on the Columbia River hydrosystem.

3 Program Framework

This program will be systematically implemented in four phases:

- *Phase I - Existing Technology.* Evaluate existing sound-based fish-guidance and deterrence systems.

- *Phase II - Technology Inventory.* Inventory existing knowledge and technology base to identify uncertainties preventing immediate application of acoustic methods and conduct research to resolve these critical uncertainties.

- *Phase III - Systems Integration and Feasibility Evaluation.* Integrate technology components identified in Phase II into a prototype fish-guidance/deterrence system and evaluate feasibility and potential effectiveness.

- *Phase IV - Full-Scale Demonstration.* Demonstrate capability of integrated sound-based fish behavior modification systems at field scales under normal facility operating conditions for extended time periods. Depending upon research progress, demonstrations will be attempted to increase bypass screen guidance efficiency, enhance surface collection, increase spill effectiveness, and redistribute fishes at scales suitable for reduction in losses to predation.

Phase I - Existing Technology

Acoustic technology exists in two areas that may partially or wholly address specific applications listed previously. First, recent advances in behavioral technologies, particularly electromechanically generated sound, have been employed by several authors with variable levels of success for several fish species. The most notable success has been achieved for applications involving the genus *Alosa* (Ross et al. 1993, Nestler et al. 1992). Less clear demonstrations of large-scale behavioral modification using electromechanical sound field generation have been shown for species of trout and salmon (Knudsen, Enger, and Sand 1994, Loeffelman, Klinect, and Van Hassel 1991). Second, the RPSH (Nestler and Davidson 1995b) and acoustic investigations (Anderson et al. 1989, Anderson 1988) suggest that acoustical fields generated hydrodynamically within intakes can be manipulated by structural means to meet fish passage objectives.

Although new technologies show promise, basic research necessary to validate these approaches across sites differing in background noise levels, hydraulic patterns, relative completion of smoltification, and dam design and operation (only some of the important variables) has not been conducted. With the exception of the electromechanical-based fish deterrence systems for *Alosa* spp., no demonstrations of fish behavioral modification at scales typical of the Columbia River system main stem dams have been performed. In cases where a specific approach appears effective, neither the underlying biological mechanisms involved in the responses of the fishes nor the adaptive values of the behavior to the signal have been conclusively shown. Even a completely successful test at one site does not resolve uncertainties sufficiently for the technology to be applied with confidence across multiple sites in the basin.

Task I-1: Identification

Existing knowledge and technology have been identified by offerers of unsolicited proposals submitted to the CE and by CE research. These unsolicited proposals, in addition to work plans to be prepared by the CE, will be technically reviewed by experts in physics of sound fields, physiology and anatomy of sound sensory systems of fish, and fish behavior. Proposal writers will be advised of technical reviewers' comments and given an opportunity to respond. The CE, Bonneville Power Administration, Indian tribes, and resource agencies will be solicited for comments on experimental designs through the FPDEP process. This phase will end with a workshop in which proposal writers will orally present their technologies to regional biologists and engineers under the review process established within the FPDEP. The proposal review panel will be funded to participate in these workshops.

Task I-2: Evaluation

Performance of each approach will be evaluated as completely as possible for sound field characteristics, site-specific influences, biological effectiveness, cost, biological mechanism of operation, and probable operations and maintenance considerations. Systems will be evaluated at one or more sites, for at least two time seasons, and for effectiveness on two races or species of salmon. Evaluations of biological effectiveness and sound field characterizations will be performed in collaboration with separate contractors or regional laboratory personnel. All technology will be evaluated under a wide range of meteorologic, wind, temperature, flow, daylight, and operational conditions representative of conditions under which the technology would be expected to perform. Success will be inferred based on statistically significant effects using multiple controls and signal on-off tests or other testing modalities. This phase concludes with a workshop coincident with the FPDEP review in

October. The workshop will include presentations by the offerers on their methods and procedures with results of the evaluations presented or copresented by independent evaluators. The expert review panel will be funded to participate in the concluding workshops.

Task I-3: Verification

Long, complex investigations of new technologies in new settings are often characterized by partial success. If any evaluated technology is partially successful (statistical significance equal to or less than $P = 0.05$ for some conditions or for some species), then that offerer will be invited to participate in ongoing program elements to develop acoustical methodologies. Success must be duplicated at additional sites, and study results must be accepted through the FPDEP review process to ensure that the technology can be used with confidence across the basin.

Phase II - Technology Inventory

Identification and classification of uncertainties are key components of program-level strategic analysis. Technology inventory has three goals: (1) systematically assess knowledge and technical base to identify uncertainties preventing immediate application of acoustic technology to meet program objectives; (2) identify critical uncertainties not tractable using the state of the art; and (3) conduct research to resolve uncertainties. Uncertainties arise during implementation planning of fish protection systems and generally result when questionable assumptions are identified. Implementation uncertainties are of three types: (1) not critical; (2) critical (an uncertainty posing significant risk to the program or resource) but probably resolvable within the state of the art; and (3) stoppers (critical with the necessary technology base not present in the state of the art). Unresolvable uncertainties are critical to program success and must be monitored as part of program risk management. The inventory phase will also serve as due diligence to avoid duplication of work already completed or under way by others.

The technology inventory phase is organized into eight task areas, each focusing on a technology component critical to implement fish protection strategies at hydropower or water control facilities. The task areas vary in their maturity. Some areas are the subject of ongoing research whereas other areas are largely unknown and characterized by a high degree of uncertainty (Table 1). Substantial knowledge, technology, and capability exist at the component level in both the private and public sector. Available technology is very advanced at the component level, particularly the generation of sound using transducers and the measurement of sound pressure in the far field. Work within each task will begin with identifying and prioritizing knowledge and technology needs followed immediately by review of existing knowledge

Table 1

Phase II Task Status Summary With Each Task Characterized by its Existing Level of Completeness and Acceptance. Estimates of the Degree of Difficulty of the Research and Probability of Successful Completion are Listed to Identify Critical Tasks or Task Components That Can Jeopardize the Program

Task > Component	Concept Maturity[1]	Hardware Availability[2]	Software Availability[3]	Professional Acceptance[4]	Difficulty of Completion[5]	Probability of Success[6]	Criticalness[7]
II-1: Sound Field Characterization							
> Far field	Mature	Off shelf	Off shelf	Accepted	Completed	High	Not critical
> Near field	Research	Prototype	α-version	In development	Moderate	High	Critical
> Extreme near field single probe & turbulence array	Research	Experimental	Conceptual	None	Difficult	Moderate (varies by setting)	Stopper-RM[8]
II-2: Characterizing Fish Hearing							
> Far field	Mature	Off shelf	Experimental	Accepted	Low	High	Not critical
> Near field	Research	Prototype	In development	In development	Moderate	Moderate	Critical
> Extreme near field	Inadequate	Preprototype	Not available	Not available	Difficult	Moderate	Stopper-RM
II-3: Target Behavior Stimulus Identification							
> Information content	Research	NA	NA	Inadequate	Moderate	Moderate	Critical
> Adaptive value	Research	NA	NA	Inadequate	Moderate	Moderate	Not critical
> Acclimation	Research	NA	NA	Inadequate	Low	High	Not critical
> Effective range	Research	NA	NA	Inadequate	Setting dependent	Low-moderate	Stopper-RM

(Continued)

[1] Mature, ongoing research, inadequate, none available.
[2] Available as off-shelf item, protoype, experimental version, in development, not available, not applicable (NA).
[3] Available as off-shelf item, β-version, α-version, experimental, in development, not available.
[4] Accepted theories or technology, in development, inadequate, none to accept.
[5] Completed, simple, moderate, difficult.
[6] High, moderate, low.
[7] Not critical (technology exists or should be easily achieved), critical (resolvable with research), show stopper (technology base not present).
[8] Requiring risk management.

Table 1 (Concluded)

Task > Component	Concept Maturity	Hardware Availability	Software Availability	Professional Acceptance	Difficulty of Completion	Probability of Success	Criticalness
II-4: Fish Behavioral Model							
> Natural settings	Research	NA	Experimental	Inadequate	Moderate	High	Critical
> Application settings	Inadequate	NA	Experimental	Inadequate	Moderate-high	High	Critical
II-5: Target Behavior Stimulus Delivery							
> Far field	Mature	Off shelf	Off shelf	Accepted	Completed	High	Not critical
> Near field	Research	Experimental	Experimental	In development	Moderate	High	Critical
> Extreme near field	Inadequate	In development	Not available	Not available	Moderate	Moderate	Stopper-RM
II-6: Behavioral Response Monitoring & Evaluation							
> Small scale	Mature	Off shelf	Off shelf	Accepted	Completed	High	Critical
> Prototype scale	Research	Experimental	Experimental	In development	Moderate	High	Critical
II-7: Assess Math/ Physical Models for Predicting Sound Fields							
> Hydraulic-physical	Mature	Off shelf	Off shelf	Accepted	Completed	High	Not critical
> Hydraulic-math	Mature	Off shelf	Off shelf	Accepted	Completed	High	Not critical
> Acoustic far field	Mature	Off shelf	Off shelf	Accepted	Completed	High	Not critical
> Acoustic near field	Inadequate	Experimental	In development	In development	Moderate	Moderate	Critical
> Turbulence	Research	In development	In development	Not available	Difficult	Low-moderate	Critical
II-8: Supplemental Behavioral Stimuli Evaluation							
> Attracting light	Mature	Off shelf	NA	Accepted	Simple	High	Critical
> Repelling light	Research	Experimental	NA	Development	Moderate	High	Critical
> Flow field	Inadequate	NA	NA	Accepted	Difficult	Low	Not critical

and technology. Potentially resolvable critical uncertainties will be integrated into the research and development activities of the program. Stoppers will receive elevated research priority and be monitored as part of program risk management. Phase II deliverables will be the individual components required for construction of integrated fish behavior modification systems.

The eight task areas of the technology inventory phase are:

- *Task II-1: Sound Field Characterization.* Identify and develop technology to measure and characterize sound fields, particularly in the extreme near field of sources where the particle motion component of sound is dominant.

- *Task II-2: Characterizing Fish Hearing.* Characterize sound detection capabilities of fish species and age groups to far-field, near-field, and extreme near-field components of sound fields.

- *Task II-3: Target Behavior Stimulus Identification.* Identify sound stimuli eliciting behavioral responses from species and age groups under static and dynamic conditions and relate to natural behavior and adaptive value. Describing acoustic fields for information content and the adaptive value of the information content from the perspective of fish sensory systems will be emphasized.

- *Task II-4: Fish Behavioral Model.* Develop comprehensive behavioral models of appropriate spatial and temporal scales for fish species and age groups in flumes and natural settings for the listed specific applications.

- *Task II-5: Target Behavior Stimulus Delivery.* Identify or develop stimulus delivery systems for static or dynamic conditions.

- *Task II-6: Behavioral Response Monitoring and Evaluation.* Identify or develop technolog: for observing fish behaviors to acoustic stimuli both under controlled laboratory and limited field-scale conditions and under long-term, full-scale monitoring conditions.

- *Task II-7: Assess Math/Physical Models for Predicting Sound Fields.* Assess math and physical models for predicting hydraulic and sound fields associated with different parts of bypass systems, collection structures, and powerhouses with emphasis on prediction of turbulent flow patterns associated with predicting extreme near-field acoustic and hydraulic conditions.

- *Task II-8: Supplemental Behavioral Stimuli Evaluation.* Explore other behavioral modification stimuli (e.g., light and large-scale flow fields) to supplement sound.

Phase III - Systems Integration and Feasibility Evaluation

Use of integrated sound systems and supplemental stimuli to meet the program objectives is immature at the system level with relatively few large-scale applications that can be used for reference. Phase III integrates concepts described in Chapter 2 with components identified in Phase II to develop protocols, hardware, and software necessary to construct fish-behavior-modification systems that function at the scale of operating hydropower and other water control facilities. Integration and feasibility testing of systems will begin with the first application group for which necessary components are available. Systems will be tested for feasibility in laboratory and controlled field tests close in scale to prototype applications to relate scale of application to system feasibility. System development will continue iteratively until a maximum or predetermined effectiveness is achieved. System evaluations will be conducted in the following environments: (a) near trashrack, turbine intakes, and bypass and vertical screens; (b) forebay spillway; (c) surface collector system; (d) juvenile bypass system; (e) reservoir; and (f) tailrace. Deliverables from Phase III will be application-specific integrated systems tested for feasibility. Phase III is composed of the following tasks.

- *Task III-1: Prioritize System Environments and Biotic Targets.* Evaluate study needs for different environments and status of technology inventory to list and prioritize potential feasibility tests. This task will be performed through the FPDEP review process.

- *Task III-2: Quantitative Specification of Biological Goal.* Specify goals for behavior modification systems quantitatively in the form of testable hypotheses. This task will be performed through the FPDEP review process.

- *Task III-3: Characterize Application Environment.* Describe the acoustic and hydraulic environment using mathematical and physical models supported with field measurements for model calibration/verification. Develop mathematical or narrative models of anticipated application-specific fish behavior.

- *Task III-4: Biological and Engineering Specifications.* Prepare an overview of system theory of operation for each target application that includes system specifications to the component level with emphasis on definition of the region to be exposed to the stimulus, the stimulus signal level relative to background, and other factors determined to be critical for the effectiveness of the system. Complete specifications for monitoring and evaluation of both the stimulus and fish behavior.

- *Task III-5: Procure Components and Complete System Integration.* Design and construct application-specific systems with appropriate documentation and testing for electronic and acoustic performance. All necessary protocols, hardware, and software will be completed in this task.

- *Task III-6: Evaluate System Feasibility.* Application-specific systems will be deployed, data will be collected for feasibility evaluation, and the resulting data will be processed and analyzed.

- *Task III-7: Technology Assessment.* Summary results of feasibility testing will be presented at a workshop held under the FPDEP review process when program progress indicates that Phase III objectives have been met. Future work or refinements to complete Phase III will be determined through this workshop. If appropriate, demonstration studies and sites will be selected for Phase IV.

Phase IV - Full-Scale Demonstration

Phase IV will test the maturity of program technology for widespread application within the basin. The demonstration phase will evaluate full-scale costs, operations and maintenance issues, and biological effectiveness. Protocols developed for Phase III will be expanded for demonstration sites. Tasking for demonstration studies will be the same as for Phase III feasibility evaluations except for modifications necessary for full-scale, long-term evaluations.

The product of Phase IV will be complete protocols and specifications for behavioral modification systems that can be installed at projects for long-term use. These specifications will form the basis for solicitation and selection of vendors of equipment and services to manufacture and install permanent behavioral modification systems at operating hydropower or other water control facilities.

4 Time Lines, Schedules, and Deliverables

The schedules and time lines shown in Figure 1 are based on receipt of funding by the last quarter of FY94. Delays in receipt of funding will result in corresponding readjustments of time lines and schedules. Time lines for tasks occurring later in the program are dependent upon research progress from earlier tasks. As the program proceeds, time lines for tasks that begin later in the program may require readjustment to account for accelerations or delays in earlier "building block" tasks.

Tasks and subtasks that are critical to the broad program objectives are identified to aid risk management. Annual reports documenting all activities will be prepared at the end of each fiscal year and submitted for review by the end of the first quarter of the immediately following fiscal year. Progress in critical tasks and subtasks will be monitored quarterly, and program-threatening delays or failures will be identified and submitted for evaluation in the immediately following quarter. The final products of the program are complete specifications for prototype systems for the specific applications identified in Chapter 1.

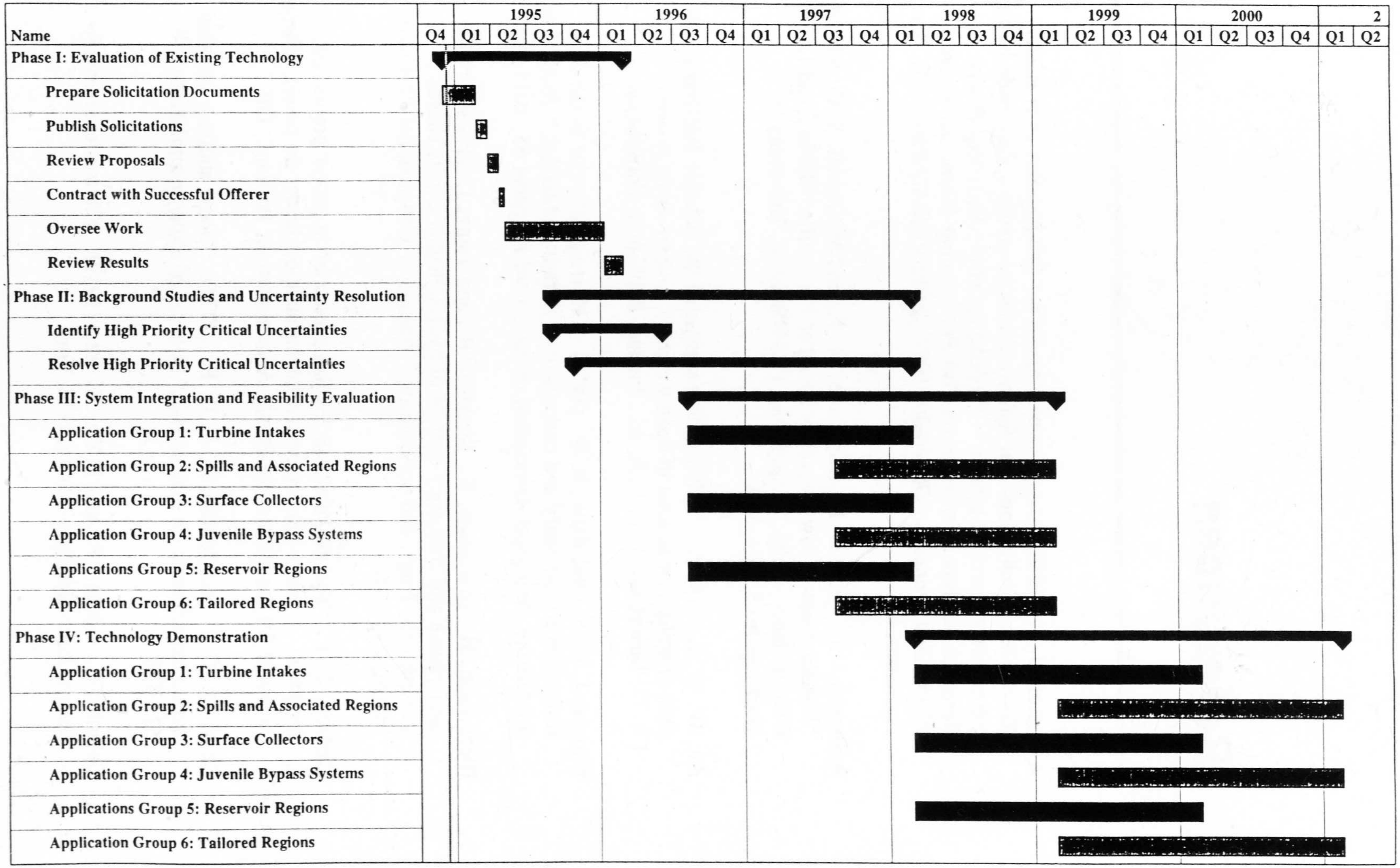

Figure 1. Schedules and time lines

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13. ABSTRACT *(Maximum 200 words)*

Aquatic environments are rich in complex sound stimuli generated by wave action, internal structures of fishes, and movements of water, aquatic biota, and substrate. The capability of fishes to detect and respond to pressure and water particle motion components of sound fields is well documented. At every stage of their migration down the Columbia River system, smolts are acquiring and processing information using their sensory systems and responding in definite, and perhaps, very predictable ways. However, understanding this capability is limited by the inadequacy of standard acoustical or hydrodynamic methods to describe pressure and particle motion components of sound fields relative to fish sensory systems. There is no ambiguity, however, that fishes possess a very well-developed, highly sophisticated sensory system employed to perform those daily functions required to sustain life. It seems unreasonable to assume that fishes abandon these behaviors when they approach dams or enter intakes.

Trade-offs between efficient hydrodynamic design of bypass system components and safe, effective fish passage may require an understanding of system sound fields relative to fish sensory systems. Recently completed research at The Dalles and McNary Dam underscores the importance of understanding sound fields generated in bypass systems relative to the sensory systems of fishes. Sound fields are generated when the high-energy flow fields of intakes are partially intercepted by screen designs that differ in structural complexity. Screen-specific differences in sound fields

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Behavioral barriers	Fish protection
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appear to produce variations in impingement characteristics. Site-specific differences in background noise levels and turbulence resulting from trashrack design, intake configuration, intake location, and powerhouse configuration probably mediate thresholds at which fish can detect sound fields generated by the screens.

The above findings and recent advances in sound-based fish protection systems together indicate that acoustic technology has matured sufficiently, or could be expected to mature sufficiently in the near future, for application in the basin. The objective of this program rationale is to systematically develop sound-based fish protection technology to improve fish protection, passage, and health during migration through the hydrosystem. Program-level effort and support would be required to develop acoustic technology for widespread use in the Columbia River basin for the following applications.

a. Increase fish-guidance efficiency of bypass screens by modifying vertical distributions.
b. Increase fish-collection efficiency of surface-oriented collectors by modifying vertical and horizontal distributions.
c. Increase effectiveness of spilling by modifying horizontal distributions.
d. Enhance efficiency of collectors located upstream of dams by modifying vertical and horizontal distributions.
e. Repel juvenile salmonids from irrigation diversions.
f. Decrease entrainment of resident reservoir fishes during generation.
g. Attract upstream migrant adults to fish ladders and counting areas.
h. Repel adults to prevent fallback through turbines after successful upstream passage.
i. Repel squawfish from forebays and smolt bypass outfalls.
j. Attract squawfish to predator removal areas.

The goal of this program is to develop acoustic technology to complement existing and planned programs having specific fish protection, passage, and health goals. The scope of this program will include both the needs and interests of the Department of Energy and the U.S. Army Corps of Engineers. The program will be coordinated and partnered as much as the specific technical needs of the two agencies allow. Partnering opportunities with natural resource agencies, universities, Indian tribes, and the private sector will be pursued. The U.S. Army Corps of Engineers Fish Passage Development and Evaluation Program process will be used for program review and coordination.

A comprehensive, systematic research and development program merging information on sound fields, sound sensory system of fishes, and behavioral response of fishes to sound stimuli will be performed to enhance fish passage, protection, and health in the Columbia River system. This program will be systematically implemented in four phases:

- *Phase I - Existing Technology.* Evaluate existing sound-based fish-guidance and deterrence systems.
- *Phase II - Technology Inventory.* Inventory existing knowledge and technology base to identify uncertainties preventing immediate application of acoustic methods and conduct research to resolve these critical uncertainties.
- *Phase III - Systems Integration and Feasibility Evaluation.* Integrate technology components identified in Phase II into a prototype fish-guidance/deterrence system and evaluate feasibility and potential effectiveness.
- *Phase IV - Full-Scale Demonstration.* Demonstrate capability of integrated sound-based fish behavior modification systems at field scales under normal facility operating conditions for extended time periods. Depending upon research progress, demonstrations will be attempted to increase bypass screen guidance efficiency, enhance surface collection, increase spill effectiveness, and redistribute fishes at scales suitable for reduction in losses to predation.