Effects of Sound on Fish

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Summary

A. Effects of Pile-Driving Sound on Fish

The purpose of this report is to describe what is known about the effects of sound (including those from pile driving activities) on fishes and to identify studies needed to address areas of uncertainty relative to measurement of sound and the response of fishes. *Exposure to sound* is defined to include both the received level and duration of the signal.

The emphasis of this report is on the *known* effects of sound *received* by fishes. The effects are known if both the received sound and its elicited effect are well defined. Detailed source characteristics of various types of piles and detailed analyses of the effectiveness of various sound attenuation technologies (e.g., bubble curtains) are beyond the scope of this report.

The results in the peer-reviewed and gray literature on the effects of sound on fishes are variable and, as yet, give no clear-cut "rules" as to what sounds will affect fish and how they will be affected. A limited number of quantitative and qualitative studies and observations show mortality related to pile driving and also provide some data pertaining to the effects of sound on fishes. Results based on sound signals other than pile driving indicate that *some* exposures to sound will cause a change in the hearing capabilities of *some* test fish species or actually damage the sensory structures of the inner ear. There is also a very limited body of evidence that leads to the suggestion that exposure to sound has the potential for affecting other aspects of the physiology of fish, and that these effects may range from the macro (destruction of the swim bladder) to the cellular and molecular.

Data from explosive blast studies, while not directly comparable to pile driving, indicate that very fast, high-level acoustic exposures can cause physical damage and/or mortally wound fishes. There is also reason to believe that lesser effects might also occur, but these have not been well documented. Just as in investigations testing the effects of sound, however, the number of species studied in tests of the effects of explosives is very limited, and there have been no investigations to determine whether blasts that do not kill fish have had any impact on short- or long-term hearing loss, or on other aspects of physiology (e.g., cell membrane permeability, metabolic rate, stress), and/or behavior (e.g., feeding or reproductive behavior, movement from preferred home sites).

While these earlier studies provide a preliminary indication of the potential impact of pile driving on fishes, there are no peer-reviewed studies that examine the effects of pile driving on fish hearing, and there are only a few non-peer-reviewed reports about effects on non-sensory structures.[2] While we are able to use available data as a very preliminary indication of the kinds of effects that might be encountered as a result of pile driving, only additional well-controlled studies of behavioral and physiological responses to pile driving or to signals specifically

[2] In the course of conducting this review, the authors reviewed numerous reports and publications provided by the Fisheries Hydroacoustics Working Group and other colleagues. We are grateful for having many important reports and papers brought to our attention and many of these have been incorporated into this report. At the same time, we have elected to not include a number of reports and papers provided to us because we did not see them as being relevant to the subject and/or scope of this report.

designed to have the same acoustic characteristics as pile driving sounds, will provide clear scientific support of any criteria that are to be established.

B. Areas of Uncertainty and Studies Needed

To date, there are few data for fish on the effects of exposure to sound from pile driving, and these only appear in the gray literature (e.g., Anderson 1990; Feist 1992; Bonar 1995; Shin 1995; Caltrans 2001, 2004; Abbott and Bing-Sawyer 2002; Nedwell et al. 2003; Abbott 2004). Although these studies provide some information about exposures to pile-driving sounds, there is little that can be definitively concluded from them. By way of example, there are data and general observations of mortality and some injury to fishes that are close to the source where the level of sound is very high. Additionally, there are observations based on the numbers of fish that come to the surface dead after pile driving that suggest that there is less (or no) mortality at greater distances from the source (where the received level of sound would be lower than close to the pile). Finally, experimental cage studies also suggest that fishes further from the pile have little or no mortality and/or damage (e.g., Caltrans 2001, 2004; Abbott and Bing-Sawyer 2002; Nedwell et al. 2003; Abbott 2004; Marty 2004).

It does appear, however, that the degree of damage is *not* related directly to the distance of the fish from the pile, but to the received level and duration of the sound exposure. Because monitoring data show that sound pressure levels do not necessarily decrease monotonically with increasing distance from the pile, it is imperative that received sound levels be measured in future studies in order to develop exposure metrics that correlate with mortality and different types of damage observed in fish exposed to pile driving. The only study we are aware of to date (Caltrans 2004) that was intended to measure the differential in survival between fish exposed to pile driving with a bubble curtain attenuation device turned on and those exposed with the bubbles turned off, was not able to show a statistical difference in survival between the two conditions because the sample sizes were too small. Though in a study using an explosive sound souce, Keevin et al. (1997) showed that use of a bubble curtain significantly reduced mortality of caged bluegill (*Lepomis macrochirus*) during demolition of a dam and locks on the Mississippi River.

It is also very difficult to extrapolate to pile driving from studies using other types of signals (e.g., pure tones, air guns) because such signals are not analyzed or described in a format that can be interpreted in terms of a pile-driving signal (e.g., acoustic energy flux or acoustic intensity over time). Moreover, signals used in other studies often differ markedly from those emitted by pile driving in terms of duration, rise and fall times, and frequency content (e.g., Yelverton et al. 1975; Hastings et al. 1996; McCauley et al. 2003). Thus, specific signal components that affect fish may be very different in, for example, a study that uses continuous white noise vs. a study that uses impact sound exposures such as generated during pile driving.

The authors of this report conclude that it is imperative to initiate studies that start with very basic questions about the effects on fishes from exposure to pile driving sound. Table 1 (page 6) gives an overview of the types of studies that need to be accomplished to better understand the issues of pile driving and the biological effects caused by such signals. Note that

this table is presented in much greater detail in Section V of this report (Table 5, page 49), and summarized in Figure 9 (page 73).

It is important to note, as discussed in detail in Section V (page 42), that the body of scientific and commercial data currently available is inadequate for the purpose of developing more than the most preliminary scientifically supportable criteria that will protect fish from exposure to pile driving sound. As a consequence, such criteria are not proposed in this report. Instead, the information from earlier blast and pure tone studies has been used to develop recommendations for interim guidance to address physical injury and mortality and damage to auditory sensory cells, while recognizing the need for well-controlled studies to provide clear direction for development of scientifically supported criteria. It is critical to note, however, that *the interim guidance developed must be used with the utmost caution*, and that such guidance should not be used for any other signal than pile driving. The interim guidance recommended for pile driving is *only* applicable to that source and not for other sources such as air guns or sonars because it is based on results of effects studies that had received signals with temporal and spectral characteristics similar to those of pile driving signals.

Table 1: Outline of studies to investigate pile driving and its effects on fishes.
Characteristics of pile driving
Define acoustic dose for exposure to pile driving sound – Develop ways to express exposure to pile driving sounds in terms of total energy received over time and degree of temporal variation, and to define the acoustic particle velocity within the sound field.
Structural acoustic analysis of piles – Develop structural acoustics models of piles to investigate how their physical characteristics affect the radiated sound and how modifications to piles could alter the sounds received by fish. Acoustic analysis could also indicate how best to describe the waveform and how it is affected by pile material, geometry and size, hammer type, and environmental factors such as water temperature, depth, and substrate. These studies could lead to a better ability to develop attenuation of sounds produced during pile driving by modifying structural material, attenuation technologies, etc., especially if they are linked to modeling of the underwater sound propagation as described below.
Characteristics of underwater sound field – Develop underwater sound propagation models for locations of interest and integrate with pile structural acoustics models to estimate received levels of sound pressure and particle velocity in the vicinity of pile driving operations and define zones of impact on fishes. Verify with field measurements of underwater sound pressure measurements.
Effects on fishes
Hearing capabilities of Pacific Coast fishes – Determine hearing capabilities (using Auditory Brainstem Response [see Glossary, page 61]) of representative species.[3]

[3] All studies involve what are called in this report "representative species." These are defined as species that serve as models for fishes in the region of question – in this case, the Pacific Coast. Species for study need to be selected to represent differences in: (a) habitat; (b) presumed hearing capabilities (e.g., hearing specialists vs. non-specialists; (c) ear structure and connections of the ear to peripheral structures such as an air bubble; (d) swim bladder presence/absence, biomechanical properties, and connection to the gut; (e) bony fish vs. non-bony fish (including elasmobranchs); (f) fish size/mass; and (g) other comparable factors. A minimum set of fishes should be defined so as to have the fewest possible studies and yet represent as many of the parameters for the fishes of the area of question as possible.

Table 1: Outline of studies to investigate pile driving and its effects on fishes.
Mortality of fishes exposed to pile driving – Determine mortality immediately and at longer intervals after exposure of representative species as a result of exposure to pile driving sounds. Measure pathology (using accepted necropsy studies) of the effects of sounds on fishes at different levels and durations of exposure.
Effects of exposure to pile driving sound on non-auditory tissues – Using precisely the same paradigm as used to study the effects on the ear, examine other tissues using standard fish necropsy and histopathological techniques to assess gross, cellular, and molecular damage to fish. Furthermore, determine stress effects on fish using appropriate stress measures (e.g., hormone levels).
Effects of pile driving sound exposure on hearing capabilities – Determine permanent hearing loss (PTS) and temporary hearing loss (TTS) on representative species.
Effects of pile driving sound exposure on fish eggs and larvae – Determine mortality, growth rates, and pathological changes in developing fishes of representative species with exposure at different times during the development cycle
Behavioral responses of fish to pile driving – Observe, in large cages, the short-term behavioral responses of representative species to pile driving sounds. (e.g., Do fish attempt to swim from the source? Do they react to the sounds? Do they "freeze" in place?)
More general behavioral responses of fish to pile driving – Determine if there are longer-term effects that might alter movement patterns of fish schools, preferences for breeding sites, feeding behavior, mating and reproductive behavior, etc.
Effects of exposure to pile driving sound on the ear and lateral line – Determine morphological changes over time for representative species on sensory cells of the ear and lateral line, and whether such changes are reversible
Effects of multiple exposures to sound from pile driving on fish – For the appropriate experiments cited above, determine effects of multiple exposures, over time, of pile driving

At the same time, it should be noted that the interim guidance provided in this report (Table 4, page 46) is conservative and protective of fish. While we do not propose a single set of numbers, the guidelines are values that are well below signal levels that are known to have damaged fishes in other experimental situations. Doing this is particularly important because most of the data providing the basis for interim guidance involved experiments that did not use pile-driving signals, and so extrapolation from such signals to pile driving is difficult, at best.

C. Terminology

This report contains a wide range of acoustic and biological terms. To facilitate understanding of terminology, most of the terms are defined in a Glossary that appears at the end of the report (page 61).

In addition, it is important to define what is meant by "behavior" in this report because the word is used for a wide range of activities, and usage varies between different investigators. For example, behavior may be used to refer to the complex interaction of signals and rituals that animals use during mating, or the movements of animals from one feeding ground to another. In the context of this report, "behavior" is used in its broadest possible sense unless otherwise qualified. In terms of pile driving, the behavioral effects may include small startle movements when the sound is heard or, at the other extreme, behavior may include changes in the reproductive rituals of fish caused by the presence of long-term pile driving at some distance which alters hormone levels.

I. Introduction

Over the past decade it has become increasingly apparent that human-generated (often called"anthropogenic") sound has the potential to impact the health and well-being of animals as well as humans. There has been, in this same time frame, an increasing awareness of the presence of human-generated sounds in the aquatic environment, and concern has arisen that these sounds could impact aquatic mammals, diving birds, fishes, amphibians, reptiles, and perhaps even invertebrates (e.g., NRC 1994, 2000, 2003; Richardson et al. 1995; Popper 2003; Popper et al. 2004).

Despite the concerns raised by increased human-generated sound in the aquatic environment, very little is known about the effects of exposure to such sounds on marine mammals, and far less is known about the effects on fishes (see reviews in NRC 1994, 2000, 2003; Popper 2003; Popper et al. 2004). And, even in cases where data are available for fishes, they are so few that one must be extremely cautious in attempting to extrapolate between species, even for identical stimuli. Moreover, one must also be extremely cautious with any attempts to extrapolate results between stimuli because the characteristics of the sources (e.g., air guns, sonars, ship noise, pile driving) differ significantly from one another.

The purpose of this report is to describe what is known about the effects of sound on fish and to identify needed studies to address areas of uncertainty relative to measurement of exposure to sound and the response of fishes. *Exposure to sound is defined to include a measure of both the received level and the duration of the signal*. For example, the received level can be expressed in terms of acoustic pressure, particle velocity, or intensity (energy flux), which all vary with time over the duration of the signal. Sound exposure metrics usually convey an integration of the received level over the time duration of a single acoustic event. The effects of multiple events primarily depend on the degree of damage caused by a single event, recovery of the damaged region during the time interval between events, and the total number of events. If a single sound exposure causes absolutely no damage whatsoever, then no damage will occur for repeated multiple exposures.[4]

The focus of this review is the evaluation of all known literature related to the effects of pile driving on fishes, with particular emphasis on fishes of the Pacific Coast region, including fishes in bay, estuarine, lake, river, and stream habitats. Pile driving commonly occurs in shallow water and is related to construction and repair of bridges, docks, and other over water infrastructure. Very little, if anything, is known about (1) particular characteristics of a pile-driving signal that are responsible for different observed effects, and (2) the differential in effects that can be attributed to differences in signals generated by different types of piles (e.g., concrete vs. steel). Indeed, structural acoustics analysis of different piles, including how variations in material and structure could alter sounds received by fish, is a recommended study (Tables 1 and 5). Moreover, only the experimental studies recommended to determine effects on fishes will reveal the relationships between characteristics of pile driving signals and observed effects. Thus the emphasis of this report is on what is known about effects related to sound received by fish, and not on the sounds emitted by any particular type of pile or pile driving operation.

[4] Although it should be noted that some effects may not be easily observed, such as damage at the cellular levels, but as a result of repeated exposures the damage may show up on a larger, and more easily determined, scale.

This report describes the potential for effects on fish that is supported or inferred from available information and sets the stage for future studies by outlining what is known about detection of acoustic signals by fishes, sound detection by Pacific Coast fishes, effects of exposure to sound on various species of fishes, and characteristics of the sounds produced by pile driving. Far too little is known about the effects on fish from exposure to sound to allow for definitive conclusions to be drawn from the literature. A series of well-defined research programs, with suitable and appropriate experimental design and controls, would help garner needed information (see Tables 1 [page 6] and 5 [page 49]).

The material presented in this report is based on a careful evaluation of technical reports (gray literature) and peer-reviewed articles (see footnote 1, page 4). The approach and analysis in each study differs, and so extrapolation between studies, especially those done in different locations or by different groups of investigators, is difficult. Moreover, we have been particularly careful in our use of the gray literature because we have no way of knowing if these studies have undergone rigorous scientific review.

To help resolve the problems in using the gray literature reports, we have attempted to review the potentially useful gray literature reports ourselves, and have used this material based on our views about the quality of the science and the validity of the conclusions in these studies. We have, for the most part, avoided use of material that is presented only as pages on the Internet because we have no basis for knowing if that material has received any review whatsoever.

In addition to primary peer-reviewed literature and gray literature reports, we also include citations to a number of reviews and overviews of various aspects of the material presented here. It must be recognized that the reviews, even if they have gone through appropriate peer review, are often the opinions of the authors and may be based on analysis of material from peer-reviewed articles and/or the gray literature.

Based on the literature review, this report provides the rationale to establish interim guidance for impact thresholds for the purpose of protecting listed and commercially important species, and identifies future research needs. Once research provides sufficient data to address identified critical information gaps such as effects on physiology and behavior, results can be used to establish formal criteria to protect fish.

The report is divided into several sections. Section I (page 8) is an overall introduction. Section II (page 10) describes the signals produced by pile driving and includes an overview of a number of the experimental studies that have explicitly looked at the effect of pile driving sounds on fishes. Section III (page 16) provides a background on sound and fish, and includes an overview of sound detection and the use of sound by fishes. This is followed in Section IV (page 25) with a discussion of what is known about the effects of exposure to sound on fishes. As appropriate, Section IV provides some analysis of the little we know about the effects of pile driving, and provides considerably more background on the effects of exposure to sounds generated by other means, including underwater sound projectors used in laboratory experiments and others more representative of human-generated sources (e.g., air guns, explosives, sonar). The discussion includes effects that range from fish mortality to the movement of fishes from areas of ensonification. Finally, Section V (page 42) describes gaps in our knowledge on the

effects of pile driving on fishes. It provides interim guidelines that might be used to help protect fishes before firmer criteria can be established based on new data that need to be obtained. Section V ends with recommendations for studies needed to develop realistic and usable criteria.

II. Characterization of Pile Driving Sound and Its Effect on Fishes

A. Overview of Pile Driving Sound

Impact sounds result from a rapid release of energy when two objects hit one another. The physical characteristics of impact sounds primarily depend on the mechanical properties of the impacting objects. When a pile-driving hammer strikes a pile, impact sound propagates in the air and a transient (stress) wave, or pulse, propagates down the length of the pile. The impact will also create flexural (or transverse) stress waves in the wall of the pile which couple with the surrounding fluids (air and water) to radiate sound into the water and additional sound into the air.

Moreover, the pulse propagating down the length of the pile couples to the substrate at the water bottom, and this causes waves to propagate outward through the bottom sediment. These transient sound waves (or pulses) in the substrate can be transmitted from the bottom into the water at some distance away from the pile to create localized areas of very low and/or very high sound pressure and acoustic particle motion because of destructive or constructive (respectfully) interference with the sound pulse traveling outward through the water directly from the pile. Thus it is possible that at certain locations received levels of sound could be higher further from the pile than at locations closer to it and this has been observed in some monitoring data (Caltrans 2001).

Sound pulses as a function of time are referred to as waveforms. The sound pressure associated with passage of a waveform at some point away from the pile can be measured at a selected location in the water column using a hydrophone (an underwater microphone) or sound level meter with an underwater probe. Typically, pile driving sounds underwater are characterized by multiple rapid increases and decreases in sound pressure over time as shown in the measured waveform displayed in Figure 1(a) (page 66). The peak pressure is the highest absolute value of the measured waveform, and can be a negative or positive pressure peak.

The root-mean-square or “rms” level is determined by analyzing the waveform and computing the square root of the average of the squared pressures over the time period that comprises that portion of the waveform containing 90 percent of the sound (pressure squared) energy (Richardson et al. 1995; Illingworth & Rodkin 2001). This calculated rms sound pressure level (SPL) is described as “RMS (impulse)” and is used to report an overall average SPL for a single pile driving pulse (Caltrans 2001; Illingworth & Rodkin 2001). The frequency content of the sound pressure level shown in Figure 1(b) provides some indication of the bandwidth of the pile driving pulse. The frequency bandwidth for pile driving sounds is typically below 1,000 Hz, the same bandwidth as hearing in many species of fish (see Fig. 2, page 67).

Another measure of the pressure waveform that can be used to describe the pile driving pulse is the sound energy. Typically, the effects of short-duration or transient sounds are not

only characterized by rise time, duration, and peak pressure, but also total energy received over time (or dose). While the effects are described most often in terms of humans, all indications are that the same effects are likely to occur in all vertebrates. The energy contained in a sound wave is a measure of the amount of work it does pushing on the fluid (or substrate material) as it travels. The sound wave "pushes" with pressure, or force acting over a unit area, and this force causes the fluid to move locally. This fluid motion is called "acoustic particle velocity." If the sound impinges on an aquatic animal, the energy will create forces and motions inside its body just as it does in the fluid.

For a plane wave traveling in open space without any interaction with objects or boundaries, the relationship between sound pressure (p) and particle velocity (v) is $p = (\rho c)v$, where ρ (kg/m^3) is the density of the fluid and c (m/s) is the speed of sound in the fluid (or other material). The acoustic energy flux or intensity (I) of a sound wave is the product of the pressure multiplied by the particle velocity, and has the units of Joule per square meter per second (J/m^2-s) or watts per square meter (W/m^2). For a plane wave the intensity (or energy flux) is given by $I = p^2/(\rho c)$. It is equivalent to the amount of energy in Joules passing through a unit area per unit time as the sound wave travels unbounded in the fluid.

How rapidly the energy accumulates over time may be significant in assessing the potential effects of exposure to transient sounds on fish and other aquatic animals (e.g., Johnson and Robinson 1969; Hamernik and Hsueh 1991). Indeed, Finneran et al. (2002) found that cumulative sound energy could be used as a criterion for temporary threshold shift in hearing of a few species of marine mammals (odontocetes) for a single exposure to several different types of transient signals. In addition, Rasmussen (1967) reported that fish could withstand higher peak pressure from a gunpowder explosion than from a dynamite explosion because of the "more rounded front" of the pressure waveform. A more rounded front would result in a slower rate of sound energy accumulation than would occur for a waveform typical of a dynamite explosion.

Because sound is a form of energy, the damage potential of a given sound environment will depend not only on its level, but also its duration. For constant sound levels this is a straightforward analysis, but if sound level varies it must be sampled repeatedly over a well-defined time window (or sampling period). In human studies, these samples have been averaged together to form a single value known as the Equivalent Continuous Sound Level or L_{eq}, which has the same energy content as a varying sound level.

A common alternative energy metric to the L_{eq} is the sound exposure level (SEL), which is defined as the constant sound level acting for one second, which has the same amount of acoustic energy as the original sound. An SEL measurement is often used as an energy metric for a single acoustic event. Because all SEL measurements are normalized to a one second time interval, it may be used to compare the energy content of different exposures to sound. SEL is calculated by summing the cumulative pressure squared (p^2) over time and is often used as an indication of the energy dose. The unit for SEL is dB re 1µPa^2-s. This metric accounts for both negative and positive pressure excursions because p^2 is positive for both and therefore negative and positive pressures are treated equivalently in the cumulative sum of p^2.

The cumulative sound pressure squared (also commonly referred to as accumulated sound energy) plotted in Figure 1(c) (page 66) provides a comparison of the differences in

estimated energy between transient waveforms because it contains aspects related to the effects of both peak pressure and rise time. If a sound pulse contains higher pressure peak amplitudes and/or faster rise and fall times, then the cumulative pressure squared will increase at a higher rate than for a pulse with lower peak amplitudes and longer rise and fall times. As previously stated, this could be significant in assessing the potential effects of exposure to transient sounds, on fish.

The caveat in using SEL is that its calculation inherently assumes a plane wave in which the acoustic energy flux (or intensity as defined above) is directly proportional to p^2. Thus in many underwater environments where the relationship between acoustic pressure and particle velocity is more complex, the true "total energy flux," will *not* be equivalent to SEL (Weston 1960; Hamernik and Hsueh 1991).

In the case of pile driving, there is rarely a plane wave because the sounds are produced in shallow water near shore with numerous boundaries and may interact with sound traveling in the substrate. These conditions produce a very complex sound field that does not have a simple relationship between sound pressure and particle velocity. Moreover, it is necessary to know the sound particle velocity because it is the stimulus that is detected by the ears of fishes (e.g., Popper et al. 2003). Because of the complexity of the sound field produced in pile driving environments, relatively simple models, such as the one developed by Dzwilewski and Fenton (2003), are not very useful in predicting the impact zones for aquatic animals. More detailed models of the acoustic environment are needed to understand where sound energy is concentrated and adequately predict impact zones for aquatic animals (Ward et al. 1998).

B. Comparison of Pile Driving Sound Waveforms with an Ideal Impulse Wave

Impulse sound is a transient sound that also arises from a rapid release of energy, usually electrical or chemical, such as from circuit breakers or explosives. Although impact and impulse sounds result from different processes, they share many characteristics: high peak overpressure, rapid rise and fall times, and relatively short durations. Thus "impulsive" and "impact" are often used interchangeably to describe many high level, short duration sounds.

The ideal impulse is mathematically described by the Friedlander wave (Hamernik and Hsueh 1991). If transient sounds, such as those produced by pile driving, could be characterized using a waveform similar to this type, then effects of pile driving on aquatic animals could potentially be extrapolated from data based on effects observed from exposure to other transient signals (e.g., explosives, air guns, sonic booms) or other transient waveforms that could be described by the Friedlander wave model. These estimates could provide a basis for developing interim guidance for exposure to sound from pile driving until more research is completed.

Figure 2 (page 67) shows an approximation of a pile driving sound using a Friedlander wave. Figures 2(a), (b), and (c) compare the temporal characteristics, sound exposure spectral density, and cumulative pressure squared over time, respectively, for the idealized and actual pile driving sound characterized in Figure 1 (page 66). These waves are very close in exposure characteristics, which indicate that the key characteristics for pile driving may be the peak

positive and negative pressures and their time durations, which are combined to calculate the cumulative pressure squared and sound exposure level (SEL).

SEL is based on the cumulative sum of the *square* of the pressure, so positive and negative pressures have equivalent contributions because the *pressure squared* is always positive. Even though a Friedlander wave does not have a large negative pressure, its SEL will be approximately the same as that of a pile-driving signal if both waveforms have the same peak pressure magnitude, and if the time interval for the rise and fall of positive pressure in the Friedlander waveform is the same as the sum of the time intervals for the rise and fall of the largest positive *and* negative pressures in the pile-driving waveform. Thus a systematic approach to approximate pile-driving signals using mathematically modeled Friedlander type waves could provide a way to determine how data, which have been obtained in effects studies using blasts or other transient sources, relate to different pile driving scenarios. Appendix A (page 74) provides a detailed explanation of the derivation of Figure 2 that could be applied to other sets of data.

A mathematical model that captures the essential characteristics of pile driving signals could also be used to investigate the effects of changes in the waveform that could be created by modifications in the structural acoustics design of the pile. Such an approach was used to investigate the reshaping of sonic booms to achieve both reduced loudness and sound exposure level (Leatherwood and Sullivan 1994).

C. Overview of Results from Recent Pile Driving Studies

There are five recent experimental studies that have examined the effects of pile driving on fish (Caltrans 2001, 2004; Abbott and Bing-Sawyer 2002; Nedwell et al. 2003; Abbott 2004). In this section we provide a very brief overview of these studies as background to the discussions that follow. An analysis of the results is provided in Section IV.E. (page 40) and Appendix B.

1. *Caltrans (2001)*

Caltrans (2001) did an assessment of impacts to fish in San Francisco Bay during a Pile Installation Demonstration Project (PIDP) leading up to the work on the San Francisco-Oakland Bay Bridge (SFOBB) East Span. The Caltrans study involved examining fish that died during exposure to pile driving operations, as well as determining the effects on shiner surfperch (*Cymatogaster aggregata*) held in cages at different distances from the pile driving source, although these results were listed as being very preliminary.

Results indicate that there was mortality caused by exposure to pile driving sounds, with dead fish of several different species found to at least 50 meters from the pile being driven. There was also an increase in catch by over flying gulls during pile driving, further indicating fish mortality. The report suggests that the use of a bubble curtain cut down on mortality, but there was no statistical demonstration of this result. Dead/dying fish showed a number of forms of damage including bleeding and damage to the swim bladder. Numbers were relatively low, reflecting difficulty in retrieving dead/dying fish and the possibility that fish did not come to the surface at all, or not until they were away from the collecting operation.

The extent of damage and mortality of caged fish was greater when the cages were closer to the source than further away. There was significant variability between experiments with the hammer used, the duration of exposure, and distance of the fish cages from the source. Insufficient numbers of exposures or animals make it difficult to reach firm conclusions, but there may be a distance effect that is possibly related to decreasing levels of the signal, though the signal levels at the test cages were not measured. Moreover, because of complexities in the underwater sound field, especially when there is also a potential contribution from energy that has traveled through the substrate interacting with the water-borne signal, it is not clear that the signal at some distance from a pile-driving source will be lower than a signal closer to the source (see Section II.A., page 10).

2. *Abbott and Bing-Sawyer (2002)*

Abbott and Bing-Sawyer (2002) investigated the effects of pile driving construction on Sacramento blackfish *(Orthodon microlepidotus)* as a surrogate for the threatened Sacramento splittail (*Pogonichthys mactolepidotus*). The authors reported significant problems with the study in that there were many uncontrolled factors as well as inadequate sample size to allow any definitive conclusions from the work. Significantly, sound levels at the test cages were not calibrated, and there was potential acoustic interference in the water that may have affected sound levels so that they could not be predicted based on any predictable attenuation from a site of known source levels.

Fish were placed in cages near a pile that was struck 43 times with the presence of a bubble curtain, and then 45 additional times after the bubble curtain was removed. The same fish were used both with and without the bubble curtain. Sound levels at the location of the fish (received sound levels) were not made. Cages were placed at five different distances from the pile, from 45 m to 850 m. At the end of the exposure, fish were removed from the cages, observed for injuries and abnormal behavior for five hours, and then placed in plastic bags and frozen on ice. Subsequently, non-microscopic necropsy was done on each fish to determine any external or internal damage resulting from exposure to the pile driving.

Results of the necropsy suggested that there was more damage to fish closer to the source than further away. At the same time, there was substantial inter-animal variation, even within the same cage, in damage revealed by gross necropsy. While the authors concluded that the damage was only found in fishes subject to 193 dB (peak) re 1 µPa sounds and that there was no damage to fishes exposed to sounds below 183 dB (peak) re 1 µPa, it must be emphasized that sound levels were extrapolated and were not actually measured at the cages. Accordingly, these conclusions are not well supported and the lack of actual measured sound levels and problems with controls and necropsy methods confound interpretation of the injury results.

No behavioral effects were seen prior to sacrifice of the fish, although the authors indicate that they did not have suitable facilities in which to observe behavior. There were no deaths of any animals at the time of removal from the cages or in the five-hour period prior to sacrifice for necropsy.

3. *Nedwell et al. (2003)*

Nedwell et al. (2003) examined the effects on caged brown trout (*Salmo trutta*) in response to pile driving at the Red Funnell's Southampton Terminal, England. Caged fish were placed at distances of 25 to 400 m from the piles being driven, with a control cage 10 km away. Animals were observed by closed circuit TV as they were exposed to pile-driving sounds. The sound levels at the various cages were not given, though the authors estimated that the level of the pile-driving signal (presumably, but not stated, as an impact operation) was 134 dB re 1 µPa (peak) at 400 m from the pile.

Behavioral results reportedly showed no reaction to vibropiling for fish as close as 25 m to the source. The behavior of animals in response to hammer pile operations were only reported for fish at 400 m from the source. These fish showed no apparent response to the pile driving. Fish injuries were only monitored for fish at 400 m. No criteria for injuries were given other than gross descriptions (e.g., hemorrhage of the eyes, rupture of the swim bladder), nor was there any analysis of any other possible injuries. The authors concluded that no injuries were observed. Data were not, however, provided for fish closer to the source than 400 m to the pile driving operation.

4. *Caltrans (2004)*

Caged fish monitoring was conducted during the San Francisco – Oakland Bay Bridge East Span seismic safety project using caged shiner surfperch (*Cymatogaster aggregata*) and steelhead (*Oncorhynchus mykiss*). Caged fish were exposed to pile-driving sounds at distances from 23 to 314 meters from the pile driving operation, with exposure durations of 1 to 20 minutes. Controls included fish that were placed in test cages and in the same locations as the test animals for 3 to 10 minutes but without exposure to pile driving (this was a shorter time period of being underwater than for fish exposed to pile driving) and fish that were never placed in cages and either transported to the test site (transport controls) or kept in the laboratory.

Fish were observed behaviorally following exposure and then held for 48 hours to monitor survival. Fish were then sacrificed by placing them in a plastic bag and freezing. Fish were thawed for necropsy, which was done rapidly (3-5 minutes). A number of fish died before the end of the 48-hour holding period. The authors report that all control animals had the same low level of trauma. They also reported that there was more trauma in animals exposed to pile driving, and lesser levels of trauma in animals exposed to pile driving in the presence of an air bubble curtain. However, no statistical difference between any effects seen in fishes exposed to pile driving with and without the presence of the air bubble curtain could be provided because the number of fish exposed while air bubble curtains were used did not provide a sufficient sample size. The authors also reported no mortalities that could be associated with exposure to pile driving.

5. *Port of Oakland Prelininary Study (Abbott 2004; Marty 2004)*

This study (Abbott 2004; Marty 2004) investigated the effects of pile driving on caged fish of three species: shiner perch, Chinook salmon, and northern anchovy. The fish were caged and lowered to about 25 feet at a location that was about 32 feet from the pile being driven. The fish were exposed to four minutes of pile driving (something over 200 impulses). The 2-foot diameter jetted concrete piles were driven using using a diesel hammer at the construction site of Berth 22 in the Port of Oakland. Following exposure, fish were returned to the surface, mortality determined, behavior observed for one-minute, and then later sacrificed using excellent pathology methodology (Marty 2004). Controls were treated in the same way as experimental animals and pathology was analyzed without the investigator knowing the treatment group of each animal examined.

The results showed no differences in mortality between sound-exposed and control animals (Abbott 2004). The investigators suggested that there were also no behavioral differences between sound-exposed and control animals, but this was based on behavioral analysis after the fish had been removed from the test cages and it is impossible to ascertain whether there were behavioral effects during sound exposure. (Moreover, no data were provided on how the behavioral analysis was performed.) The pathological analysis (Marty 2004) showed no difference between sound-exposed and control animals.

III. Biology of Fishes

A. Fishes of the Pacific Coast and River Systems

The fishes of the Pacific Coast region that are potentially impacted by pile driving in estuaries, bays, lakes, streams and rivers are listed in Table 2 (page 17). There is a wide diversity of species that include both cartilaginous fishes (sharks and rays – class Chondrichthyes), and bony fishes (class Osteichthyes). The bony fishes include the more advanced teleosts (ray-finned fishes such as salmon, tuna, perch, and most commercially important species), as well as representatives of more primitive chondrostean fishes, including sturgeons. The vast majority of fish species on the Pacific Coast (as throughout the world's oceans and fresh water systems) are teleosts. (Indeed, teleost fishes make up approximately 23,000 of about 27,000 extant fish species [Helfman et al. 1997]. It is worth noting that the number of living species of fish far exceeds the number of living species of all other vertebrate groups *combined*.)

Among these fishes, several are listed as threatened or endangered under the federal Endangered Species Act. These include several species of the genus *Oncorhynchus* (chinook salmon, coho salmon, chum salmon, and steelhead), bull trout (*Salvelinus confluentus*) delta smelt (*Hypomesus transpacificus*), and the tidewater goby (*Eucyclogobius newberry*). The salmonids and the smelt are all in the taxonomic order Salmoniformes, while the goby is unrelated to salmonids.

B. Fish Hearing and Its Importance

There is a long historic record of human awareness that fishes produce and use sounds in a wide variety of behaviors (reviewed in Moulton 1963). Studies of fish hearing and sound production (bioacoustics), and the importance of sounds to the lives of fishes, were not initiated, however, until the early part of the 20th century (see Moulton 1963 and Tavolga 1971 for historic reviews). The level of investigation of fish hearing and sound production (e.g., bioacoustics) increased considerably in the second half of the 20th century (see Popper and Fay 1999; Zelick et al. 1999; Popper et al. 2003; Ladich and Popper 2004).

Table 2: Target Fish Species for Acoustic Exposure Criteria in Pacific Estuaries, Bays, and Rivers (Data provided by Warren Shaul of Jones and Stokes Associates)

Species	Estuarine Life Stages	Riverine/freshwater Life Stages
	(A-adult, E-egg, L-larvae, J-Juvenile)	
Priority 1: ESA Listed Species		
Chinook Salmon *Oncorhynchus tshawytscha* (Salmonidae)*	A, J	A, E, L, J
Coho Salmon *Oncorhynchus kisutch* (Salmonidae)*	A, J	A, E, L, J
Chum Salmon *Oncorhynchus keta* (Salmonidae)*	A, J	A, E, L, J
Steelhead *Oncorhynchus mykiss* (Salmonidae)*	A, J	A, E, L, J
Cutthroat Trout *Oncorhynchus clarkii* (Salmonidae)*	A, J	A, E, L, J
Bull Trout *Salvelinus confluentus* (Salmonidae)*	A, J	A, E, L, J
Delta Smelt *Hypomesus transpacificus* (Osmeridae)*	A, J	A, E, L, J
Tidewater Goby *Eucyclogobius newberry* (Gobiidae)**	A, E, L, J	A
Priority 2: EFH Species (species listed under ESA are not listed again in EFH)		
Puget Sound Pink Salmon *Oncorhynchus gorbuscha* (Salmonidae)*	A, J	A, E, L, J
Leopard Shark *Triakis semifasciata* (Triakidae)	A, J	
Soupfin Shark (Tope) *Galeorhinus galeus* (Triakidae)	A, J	
Spiny Dogfish *Squalus acanthias* (Squalidae)	A, J	
California Skate *Raja inornata* (Rajidae)	A, J, E	
Big Skate *Raja binoculata* (Rajidae)	A, J, E	
Longnose Skate *Raja rhina* (Rajidae)	A	
Ratfish *Hydroglagus coliei* (Chimaeridae)	A, J, E	
Lingcod *Ophiodon elongates* (Hexigrammidae)**	A, J, E, L	
Cabezon *Scorpaenichthys marmoratus* (Cottidae)**	A, J, E, L	
Kelp Greenling *Hexagrammos decagrammus* (Hexigrammidae)**	A, J, E, L	
Pacific Cod *Gadus macrocephalus* (Gadidae)**	A, J, E, L	
Pacific Whiting (Hake) *Merluccius productus* (Merlucciidae)**	A, J, E, L	
Sablefish *Anoplopoma fimbria* (Anoplopomatidae)**	J	
Black Rockfish *Sebastes melonops* (Scorpaenidae)**	A, J	
Bocaccio *Sebastes paucispinus* (Scorpaenidae)**	J, L	
Brown Rockfish *Sebastes auriculatus* (Scorpaenidae)**	A, J, E, L	
Calico Rockfish *Sebastes dalli* (Scorpaenidae)**	A, J	
California Rockfish *Scorpaena guttata* (Scorpaenidae)**	J, L	
Canary Rockfish *Sebastes pinniger* (Scorpaenidae)**	A?, J	
China Rockfish *Sebastes nebulosus* (Scorpaenidae)**	A, J	
Copper Rockfish *Sebastes caurinus* (Scorpaenidae)**	A, J, E, L	
Darkblotched Rockfish *Sebastes crameri* (Scorpaenidae)**	A, J	
Greenstripe Rockfish *Sebastes elongatus* (Scorpaenidae)**		
Kelp Rockfish *Sebastes atrovirens* (Scorpaenidae)**	J	

Species	Estuarine Life Stages	Riverine/freshwater Life Stages
	(A-adult, E-egg, L-larvae, J-Juvenile)	
Quillback Rockfish *Sebastes maliger* (Scorpaenidae)**	A, J, E, L	
Redbanded Rockfish *Sebastes babcocki* (Scorpaenidae)**	A	
Redstripe Rockfish *Sebastes proriger* (Scorpaenidae)**		
Rosethorn Rockfish *Sebastes helvomaculatus* (Scorpaenidae)**	A, J	
Rosy Rockfish *Sebastes rosaceus* (Scorpaenidae)**		
Rougheye Rockfish *Sebastes aleutianus* (Scorpaenidae)**	A, J?	
Sharpchin Rockfish *Sebastes zacentrus* (Scorpaenidae)**	A, J?	
Shortspine Thornyhead *Sebastolobus alascanus*	A, J	
Splitnose Rockfish *Sebastes diploproa* (Scorpaenidae)**	A, J	
Stripetail Rockfish *Sebastes saxicola* (Scorpaenidae)**	A	
Tiger Rockfish *Sebastes nigrocinctus* (Scorpaenidae)**	A, J	
Vermillion Rockfish *Sebastes miniatus* (Scorpaenidae)**	A, J	
Yelloweye Rockfish *Sebastes ruberrimus* (Scorpaenidae)**	A	
Yellowtail Rockfish *Sebastes flavidus* (Scorpaenidae)**	A, J	
Arrowtooth Flounder *Atheresthes stomias* (Pleuronectidae)**	A, J	
English Sole *Parophrys vetulus* (Pleuronectidae)**	A, J, E, L	
Pacific Sanddab *Citharichthys sordidus* (Bothidae)**	J, E, L	
Butter Sole *Pleuronectes isolepis* (Pleuronectidae)**	A, J	
Curlfin Sole *Pleuronichthys coenosus* (Pleuronectidae)**	A	
Dover Sole *Microstomus pacificus* (Pleuronectidae)**	A, J	
Flathead Sole *Hippoglossoides elassodon* (Pleuronectidae)**	A, J	
Petrale Sole *Eopsetta jordani* (Pleuronectidae)**	A, J	
Rex Sole *Glyptocephalus zachirus* (Pleuronectidae)**	A	
Rock Sole *Pleuronectes bilineatus* (Pleuronectidae)**	A, J	
Sand Sole *Psettichthys melanostictus* (Pleuronectidae)**	A, J	
Starry Flounder *Platichthys stellatus* (Pleuronectidae)**	A, J, E, L	
Northern Anchovy *Engraulis mordax* (Engraulidae)**	A, J	
Pacific Chub Mackerel *Scomber japonicus* (Scombridae)**	A, J	
Jack Mackerel *Trachurus symmetricus* (Carangidae)**	A, J	
Pacific Sardine *Sardinops sagax* (Clupeidae)*	A, J	
Market Squid *Loligo opalescens*	A, J	
Priority 2: Other Commercial Species		
Pacific Herring *Clupea pallasii* (Clupeidae)*	A, J, E, L	
Priority 3: Sensitive Native Species		
White Sturgeon *Acipenser transmontanus* (Ascipenseridae)*	A, J	A, J, E, L
Golden Trout *Oncorhynchus aguabonita* (Salmonidae)*		A, J, E, L
Green Sturgeon *Acipenser medirostris* (Ascipenseridae)*	A, J	A, J, E, L
Longfin Smelt *Spirinchus thaleichthys* (Osmeridae)*	A, J	A, E, L
Tule Perch *Hysterocarpus traskii* (Embiotocidae)**		A, J
Shiner Perch *Cymatogaster aggregate* (Embiotocidae)**	A,J	
Pile Perch *Rhacochilus vacca* (Embiotocidae)**	A,J	
Barred Surfperch *Amphistichus argenteus* (Embiotocidae)**	A,J	
Splittail *Pogonichthys macrolepidotus* (Cyprinidae)*	A,J	A,E,L,J
Sacramento Blackfish *Orthodon microlepidotus* (Cyprinidae)*		A,E,L,J
Priority 4: Nonnative Sport-Fishery Species		
American Shad *Alosa sapidissima* (Clupeidae)*	A, J	A, J, E, L

Species	Estuarine Life Stages	Riverine/freshwater Life Stages
	(A-adult, E-egg, L-larvae, J-Juvenile)	
Channel Catfish *Ictalurus punctatus* (Ictaluridae)*		A, J, E, L
Striped Bass *Morone saxatilis* (Percichthyidae)**	A, J	A, J, E, L
Bluegill *Lepomis macrochirus* (Centrarchidae)**		A, J, E, L
Redear Sunfish *Lepomis microlophus* (Centrarchidae)**		A, J, E, L
White Crappie *Pomoxis annularis* (Centrarchidae)**		A, J, E, L
Black Crappie *Pomoxis nigromaculatus* (Centrarchidae)**		A, J, E, L
Largemouth Bass *Micropterus salmoides* (Centrarchidae)**		A, J, E, L
Small mouth Bass *Micropterus dolomieui* (Centrarchidae)**		A, J, E, L
*Physostomous (see Glossary, page 61) **Physoclistous (see Glossary)		

It was also in the latter part of the 20th century that investigators became more acutely aware of the possibility that human-generated sounds may have an effect on the lives of aquatic organisms (see reviews in NRC 1994, 2000, 2003; Richardson et al. 1995), and that the species affected not only include marine mammals (the subjects of greatest interest) but also fishes and other aquatic vertebrates (e.g., marine turtles, aquatic and diving birds) and possibly invertebrates (e.g., crabs, lobsters). The concerns about potential effects of exposure to human-generated sounds include impacts on communication with conspecifics (members of the same species), effects on stress levels and the immune system, temporary or permanent loss of hearing, damage to body tissues, mortality, and mortality or damage to eggs and larvae. Moreover, concerns not only include immediate effects, but also potential long-term effects that might now show up for hours, days, or even weeks after exposure to sounds.

1. *Sound Production and Communication*

Teleost fishes produce sound in several ways, none of which involves a larynx or syrinx-like structure as used by terrestrial vertebrates. Instead, fishes use a variety of different methods to produce sounds that range from moving two bones together to more complex mechanisms involving exceptionally fast muscles connected to the swim bladder. In this latter instance, the muscles contract at frequencies high enough to produce sound (see Zelick et al. 1999). The gas-filled swim bladder (or gas bladder) in the abdominal cavity may serve as a sound amplifier (although it has other very critical functions as well -- see Steen 1970). Sounds produced in this way usually have most of their energy below 1,000 Hz.

Fish use sounds in a wide variety of behaviors including aggression, protection of territory, defense, and reproduction (reviewed in Tavolga 1971; Demski et al. 1973; Zelick et al. 1999). There is also evidence that at least one species of marine catfish (*Arius felis*) uses a form of "echolocation" to identify objects in its environment by producing low frequency sounds and listening to their reflections from objects (Tavolga 1976). Data in the literature suggest that it is the temporal pattern of fish sounds, rather than their frequency spectrum, that is most important for acoustic communication by fishes (Winn 1964; Spanier 1979).

2. *Hearing Capabilities of Fishes*

Fishes are able to detect and respond to a wide range of sounds. The techniques for determining hearing capabilities of fishes are similar to those used in studies of other animals, or even humans. One set of measures involves "asking" a fish what it hears and then measuring some kind of behavioral response from the animal whenever a sound is detected. Such responses may be conditioned (trained, such as hitting a paddle when a sound is detected) or unconditioned (untrained, such as change in heart rate). Alternatively, the response of the fish can be determined by measuring electric potentials in the brain that are generated when the ear detects a sound (i.e., the Auditory Brainstem Response or ABR), much as is done to measure whether new born human babies are able to detect sounds.

In either case, the first goal of measuring hearing is to determine the range of frequencies (or bandwidth) that a fish can detect, and then determine the lowest levels of the sound detected at each frequency (the "threshold," or lowest signal that an animal will detect in some statistically determined per cent of signal presentations – most often 50%). The graphic representation of the threshold as a function of frequency is called an "audiogram." Figure 3 (page 68) shows audiograms for fishes similar to those found in the Pacific Coast region, or that have ears with similar structures to a number of those species.

Several aspects of fish hearing are apparent from Figure 3.[5] The figure clearly shows that species differ in the range of frequencies, or bandwidth, that they are able to detect, and in the lowest sound pressure level (threshold) that they are able to detect. The fish with the ability to detect the widest bandwidth is the scaled sardine, a species that is probably representative of the sardines and anchovies on the Pacific Coast. Greatest sensitivity (lowest threshold of detection) is found in the Atlantic cod, a relative of the Pacific cod.

While not as extensively studied, a variety of behavioral and physiological investigations of fish hearing show that a number of species (and perhaps all) have the same basic acoustic capabilities as other vertebrates, including mammals (see Popper et al. 2003 and Ladich and Popper 2004 for review of fish hearing capabilities). For example, fishes are able to discriminate between sounds of different magnitudes or frequencies, detect a sound in the presence of other signals, and determine the direction of a sound source (sound source localization). Indeed, these higher level capabilities are far more important to a fish than just detection of sound (as illustrated by the threshold measures) because fishes must discriminate between sounds of predator vs. those of prey, determine the direction of a sound emitted by potential predators or prey, and determine the nature of one sound source in the presence of others. Most importantly, fishes must detect the presence of a signal that is important to them even when there are

[5] A critical caveat to the threshold data presented in Figure 3 (page 68) arises from the acoustics of the experimental tanks in which data were obtained, how the test signals were calibrated, and the hearing mechanisms of the species studied. As discussed in detail in the text, hearing "generalists" appear to primarily detect the particle motion component of the sound field. Producing a controllable particle motion signal in a small tank (as used in most, if not all, of the earlier studies on fish hearing) is very difficult, and such signals were rarely calibrated. Thus, while the data in Figure 3 and in earlier works are often presented in terms of sound pressure, the more important question for fishes without hearing specializations is their response to particle motion, and these data are not available. While the general frequency hearing range for the species presented is valid, and the sensitivity a reasonable general indicator of hearing capabilities of generalists, future studies need to involve much better control over the acoustic signal used in determining thresholds and better calibration of signals.

extraneous background noises. Clearly, addition of human-generated sounds to the background noise can make the environment so loud that fish are not able to detect important signals (e.g., that of a predator) because of the strong anthropogenic masking sound.

It has generally been agreed that fish can be divided into two groups – hearing generalists (or "non-specialists") and hearing specialists (see Popper et al. 2003 and Ladich and Popper 2004 for detailed discussion).[6] These groups are not related to the taxonomic relationship between fishes. Instead, both hearing specialists and generalists are found distributed through many fish taxonomic groups.

Hearing specialists have special adaptations that enhances their hearing bandwidth and sensitivity (i.e., lower their hearing threshold) (see page 24 for a discussion of hearing mechanisms). Examples of specialists include goldfish, catfish, some squirrelfish, herrings and relatives, and many other taxonomically diverse species. Quite often, hearing specialists will detect signals up to 3,000 – 4,000 Hz, with thresholds that are 20 dB or more lower than the generalists. The Pacific Coast fishes that are known hearing specialists are the sardine and related species (taxonomic order Clupeiformes - e.g., herrings, shads, menhaden, anchovies). While it is likely that there may be other hearing specialists among Pacific Coast fishes, this cannot be determined without additional experimental studies on hearing capabilities of these species.

The majority of fishes do not have specializations to enhance hearing and are therefore called hearing generalists (e.g., Popper et al. 2003; Ladich and Popper 2004). Based on what we know about the ears and auditory systems of species related to those on the Pacific Coast, we can tentatively conclude that the majority of the native fishes on the Pacific Coast are hearing generalists. Moreover, the auditory anatomy of the ears of some of these species indicates that they are most likely generalists.

At the same time, it must be pointed out that data on hearing capabilities exist for perhaps only 100 of the 27,000 or more extant species of fish (see Popper et al. 2003) and so any extrapolation of hearing capabilities between different species, and especially those that are taxonomically distant, must be done with the greatest caution. Thus, studies of hearing capabilities of at least a number of the species on the Pacific Coast may be of considerable value in trying to understand whether or not the sounds generated by pile driving are within the hearing range of the species in question, and whether there are other hearing specialists in the region.

The species for which hearing capability data should be obtained must not only provide insight into their own hearing capabilities but also provide insight into related species. Thus, the species studies should include those that vary in auditory system structure (e.g., ear) and in other ways, such as whether the fish has a swim bladder or not, and if the swim bladder is or is not connected to the gut for gas exchange (physostomus vs. physoclistus – see Glossary, page 61). To facilitate data acquisition, the best approach is to use physiological recordings from the brain (the aforementioned ABR) as opposed to the far more time-consuming behavioral studies done in the past that involved training animals to perform behavioral tasks when they heard sounds.

[6] Despite this division into "specialists" and "non-specialists," it is becoming more apparent as we gain more knowledge of fish hearing that there may be a "continuum" of hearing capabilities in fish with "specialist" and "non-specialist" being the opposite ends of the continuum.

As indicated above, there are no data on hearing capabilities of any of the fish species in Pacific Coast estuaries and bays that are potentially of concern with regard to human-generated sound (Table 2, page 17), although there are data for one or two species of lesser concern such as the American shad (*Alosa sapidissima*) (reviewed in Ladich and Popper 2004). It is likely that the hearing generalists among this group of fishes detect sounds only to 1,000 – 1,500 Hz. Studies of hearing capabilities (albeit very limited and very much in need of replication) suggest that the sharks and rays probably do not detect sounds at frequencies above 800 to 1000 Hz (e.g., Banner 1967; Nelson 1967; Myrberg 2001; Casper et al. 2003). Moreover, sturgeon is an unknown with regard to hearing capabilities.

There are no reliable hearing data on mackerels or rockfish, and it is not possible to predict their hearing capabilities based on morphology because there are no appropriate morphological data in the literature. The only even remotely related data available are for the Japanese horse mackerel (*Trachurus japonicus*), which is reported to be able to detect sounds from 70 to 3,000 Hz (Chung et al. 1995).[7]

The very limited data in the literature on plaice and other related species of flatfish suggest that the Pacific Coast species are likely to have poor hearing sensitivity (high thresholds) and a relatively narrow bandwidth. For example, Chapman and Sand (1974) reported that the plaice, *Pleuronectes platessa*, is able to detect sounds at frequencies up to 200 Hz. In contrast, Zang et al. (1998) suggest that the marbled sole (*Pleuronectes yokohamae*) can detect sounds to 1,000 Hz with lowest thresholds at around 300 Hz. This relatively poor hearing capability is likely related to these fishes not having a swim bladder, a structure that appears to widen the bandwidth and lower auditory thresholds in many species.

Salmonids are one of the most important groups of fish because of their ESA listed status and commercial value, and yet the extent of data on their hearing is limited to the Atlantic salmon (*Salmo*). Hawkins and Johnstone (1978) showed that this species can detect sounds to frequencies somewhat above 600 Hz (unpublished data on the rainbow trout [the land-locked version of steelhead, *Onchorhyncus mykiss*] shows hearing capabilities that are similar to those for *Salmo* [Popper et al. in prep. a]), while more recent data show that *Salmo* are also able to detect sounds to well below 20 Hz (Knudsen et al. 1992, 1994). It has been suggested that their response to sound at frequencies generally below about 35 Hz could be useful as a way of keeping fish from entering small areas such as irrigation ditches (Knudsen et al. 1994). It appears, however, that these fish only respond when they are very close to the infrasound source, most likely because very low-frequency sound will not propagate in shallow water (Rogers and Cox 1988).

One must be careful about extrapolating from Atlantic salmon to Pacific Coast salmonids. Data on the anatomy of the ear of several salmonid species (Popper 1976, 1977)

[7] This work, and that of Zhang et al. on flatfish were only seen in abstract form and it was therefore not possible to determine the methods used in the study, which was written in Japanese. The hearing bandwidth of the mackerel in the Chung study is substantially wider than for any other non-specialist fish. Moreover, the bandwidth for the flounder reported by Zhang et al. (1998) is far wider than that reported for another species of the same genus by Chapman and Sand (1974). Therefore, without a careful analysis of the methods and results these data must be viewed with considerable caution.

suggest that the auditory system is similar in all salmonids, and this is supported by recent work on the rainbow trout (*Oncorhynchus mykiss*) (Popper et al. in prep. a) a member of the same genus as many ESA listed Pacific Coast salmonids. Still, without at least some additional hearing data this extrapolation must be done with considerable caution. Thus, it would be of great value to have hearing data on at least a few of the species in Pacific Coast aquatic habitats. Moreover, such data would be of particular value if it were for animals of different life stages and sizes since it is possible that hearing capabilities change with age and/or size of the fish, as has been suggested for the hake, a relative of the cod (Lombarte and Popper 1994, 2004). Thus, a strategy to select fish of different size, life history, and morphology for future studies, should be considered.

At the same time, the specific species to study would depend on their regulatory status and factors that could be decided later. The critical point to make is that we have too few data on hearing in any of the groups of fishes found in the Pacific Coast region, and there are not even data in the literature on related species from which it would be possible to cautiously extrapolate to most of the Pacific species.

3. *Auditory Structures*

The basic mechanism for transduction of sound into electrical signals compatible with the nervous system is the sensory hair cell (Fig. 4, page 69). This cell is ubiquitous in the ears of all vertebrates. The same cell is also found in the lateral line system, a series of receptors along the body of the fish that detects water motion relative to the fish that arise from sources within a few body lengths of the animal (e.g., Coombs and Montgomery 1999; Popper et al. 2003) (see page 40 for a discussion of the lateral line).

The body of the sensory hair cell is typical of most other cells; however, the hair cell also has an apical group of projections called the ciliary bundle that extends above the surface of the epithelium in which the cell lies (the sensory epithelium, often referred to as the “macula”). Bending of the ciliary bundle causes the opening of very tiny channels in the cilia and the entry of ions from the surrounding fluid into the cell (e.g., Hudspeth and Corey 1977). This produces a series of very rapid chemical events that culminate in the release of chemicals called neurotransmitters from the cell body. These neurotransmitters then stimulate the neurons that contact (innervate) the sensory cells. The neurons, in turn, send electrical signals to the brain that provide information about the sound.

Fishes, like other vertebrates, have two inner ears that lie within the cranial (brain) cavity just lateral to the brain as shown in Figure 5 (page 70). Unlike terrestrial vertebrates, fishes have no middle or external ear. The structure of the fish inner ear is similar to that found in all other vertebrates (Ladich and Popper 2004). The basic mechanisms of stimulation of the hair cells in the inner ear, and the conversion of acoustic energy to electrical signals compatible with the nervous system, are the same in all vertebrates.

The inner ear (Fig. 6, page 70) has three semicircular canal ducts, which are small tubes that lie in nearly orthogonal planes to one another. These canals serve to detect angular acceleration (e.g., rotational acceleration of the head) in fishes just as they do in terrestrial

vertebrates. In addition, fishes have three fluid-filled otolith organs (utricule, saccule, and lagena), each of which contains a dense calcified otolith that overlies a sensory epithelium that contains numerous sensory hair cells. These otolith organs subsume two roles for fish. First, they serve as vestibular organs and measure the position of the head in the vertical direction relative to gravity and in other directions relative to the acceleration of the body, just as they do for terrestrial vertebrates. Second, they are involved in sound detection. The earliest work suggested that the primary auditory end organs in fishes were the saccule and lagena, but there is a growing body of evidence that now suggests that all three of the otolithic end organs have roles in hearing (reviewed in Popper et al. 2003; Ladich and Popper 2004).

Each otolithic end organ may have many thousands of sensory hair cells. Fishes, unlike most tetrapods other than amphibians, continue to produce sensory hair cells throughout much of their lives (Lombarte and Popper 1994, 2004; Higgs et al. 2003). In addition, there is evidence that fishes, unlike mammals, can replace sensory cells that have been damaged as a result of exposure to certain drugs (Lombarte et al. 1993), although there have been no studies to determine if fishes can replace sensory cells that have been killed as a result of exposure to sound.

4. *Hearing Mechanisms*

Hearing is based on the detection of the mechanical motions in the medium imparted by sound. In fishes, the otolith organs are stimulated directly by the acoustic particle velocity associated with underwater sound fields. In addition, the organs can be stimulated indirectly by particle motions created when sound pressure fluctuations are transformed into motion by a gas-filled accessory organ such as the swim bladder (see below).

In effect, hearing is based on relative motion between the fish's body and the otolith. As indicated earlier, the sensory hair cells have an apically located tuft of "cilia" (Fig. 4, page 69). Because the body of fish is primarily composed of water, it will move at approximately same amplitude and phase as the impinging sound. The otoliths, however, are stiffer and about three times denser than the rest of the body (including the sensory epithelium). Thus, the otoliths will move at different amplitude and phase from that of the epithelium, and this differential motion causes the intervening ciliary bundles on the sensory hair cells embedded in the epithelium to move, resulting in the detection of sound.

Similarly, the air-filled swim bladder (or other gas bubble in the body) will be stimulated by the pressure component of the sound field. The swim bladder then serves as a small transducer that re-radiates energy in the form of particle motion, which is again detectable by the inner ear.

In hearing generalists, the primary acoustic energy is provided by the direct stimulation of the ear, though it is possible that some additional energy is re-radiated from the swim bladder and that this could lower hearing thresholds and/or increase the bandwidth of detection. As a result, hearing generalists are likely to primarily be sensitive to the particle motion component of the sound field. While earlier studies (e.g., Fig. 3, page 68) tend to report hearing data in terms of

pressure, it will be important that future studies examine the response of fish to particle motion in order to get a fuller, and more accurate, assessment of hearing capabilities of these fishes.

In contrast to hearing generalists, hearing specialists have evolved a number of different mechanisms to acoustically couple the swim bladder (or other gas-filled structure) to the ear, thereby allowing the auditory systems to detect the pressure component of the sound field. These mechanisms directly transmit motion of the swim bladder or other gas-filled structure, which is induced by sound pressure, to the inner ear, thereby providing a substantial pressure input to supplement the direct detection of particle displacement. This coupling increases hearing sensitivity (i.e., lowers thresholds) and bandwidth of detection as compared to generalists (see Popper et al. 2003 for review).

Specializations that enhance hearing vary among different species. They may range from having an extension on the swim bladder that has its rostral termination very close to the ear, as in some croakers and drums (family Sciaenidae) (Ramcharitar et al. 2001) to a direct mechanical connection between the swim bladder and ear as found in the otophysan fishes (catfish, goldfish, and relatives). Finally, there are some species that have an extension of the swim bladder, or a separate bubble of gas, that is tightly associated with the ear, or which lies near the ear (e.g., all herrings and shads and relatives, mormyrids).

IV. Effects on Fish from Exposure to Sound

Interest in the effects of human-generated sound on aquatic organisms has grown considerably in the past decade (e.g., NRC 1994, 2000, 2003; Richardson et al. 1995; NRDC 1997). While these reports, and a handful of research studies, have primarily focused on marine mammals, several have raised the issue that sounds that potentially affect marine mammals may also affect other aquatic organisms, including fishes and invertebrates (e.g., NRDC 1994, 2000; Popper 2003; Popper et al. 2004). The basis for concern about the potential effects of sound on fishes is the well-documented effects of exposures to sound on behavior, hearing, and overall physiology in terrestrial animals and humans (Lenhardt 1986; NIH 1990). While this extrapolation is certainly valid, there is also a more direct, albeit limited, body of literature that demonstrates the effects of exposure to sound on fishes, including the aforementioned observations that sound from pile driving can injure and even kill fish close to the source. These more specific studies are the basis of the following discussion.

Results of the few peer-reviewed studies on the effects of sound on fishes are discussed in this section. The specific studies are outlined, by type, in Table 3 (page 26) to give an overview of the investigations and *to show gaps* in the literature that must be filled if we are to understand overall effects of sound on fishes, and the specific effects of exposure to sounds produced by pile driving. The information in this table should be used with that found in Table 4 (page 46) to understand specific needs with regard to identifying potential effects of pile driving on fish.

A. Behavioral Responses and Masking of Biologically Relevant Sounds

There have been very few studies of the effects of anthropogenic sounds on the behavior of fishes. Data are lacking not only on the immediate behavioral effects on fishes close to a source, but also effects on fishes further from the source. Moreover, nothing at all is known about the long-term effects of pile driving on fish behavior or the effects of cumulative exposure to loud sounds.

Several studies have demonstrated that human-generated sounds may affect the behavior of at least a few species of fish. For example field studies by Engås et al. (1996) and Engås and Løkkeborg (2002), while not actually observing the behavior of fish per se, showed that there was a significant decline in catch rate of haddock and cod that lasted for several days after termination of air gun use, after which time the catch rate returned to normal. The authors concluded that the catch decline resulted from the sound of the air guns, and that the sound probably caused the fish to leave the area of ensonification, although there was no direct data to support this conclusion. More recent work from the same group (Slotte et al. 2004) showed parallel results for several additional pelagic species including blue whiting and Norwegian spring spawning herring. Slotte et al. found that fishes in the area of the air guns appeared to go to greater depths after insonification[8] compared to their vertical position prior to the air gun usage. Moreover, the abundance of animals 30-50 km away from the ensonification increased, suggesting that migrating fish would not enter the zone of seismic activity. A non-peer reviewed report by Gausland (2003), however, suggests that the declines in catch rate observed in these studies may have resulted from other factors and are not statistically different than the normal variation in catch rates over several seasons.

Similarly Skalski et al. (1992) showed a 52% decrease in rockfish catch when the area of catch was exposed to a single air gun emission at 186-191 dB re 1 μPa (mean peak level) (see also Parsons 1987; Pearson et al. 1992) They also demonstrated that fishes would show a startle response to sounds as low as 160 dB, but this level sound did not appear to elicit decline in catch.

Table 3: Citations of selected studies examining the effects of exposure to sound on fishes that have most relevance to pile driving. ***Note that there are no data for non-teleosts (e.g., sturgeon, elasmobranchs).***

Issue	Hearing Generalists	Hearing Specialists
Mortality	Yelverton et al. 1975 (guppy, bluegill, trout, bass, carp; explosive blasts)	Yelverton et al. 1975 (goldfish, catfish, minnow; explosive blasts) Hastings 1995 (goldfish and gouramis; pure tones)
Physical Injury	Yelverton et al. 1975 (guppy, bluegill, trout, bass, carp; explosive blasts) Govoni et al. (2003) (larval fish; explosive blasts, no pathology seen)	Yelverton et al. 1975 (goldfish, catfish, minnow; explosive blasts) Hastings 1995 (goldfish and gouramis; pure tones)
Auditory Tissue Damage	Enger 1981 (cod; pure tones, 1 – 5 hr) Hastings et al. 1996 (oscar; pure tones, 1 hr) McCauley et al. 2003 (pink snapper, air gun)	Hastings 1995 (goldfish; pure tones, 2 hr)

[8] See glossary under "ensonification" for differentiation between ensonification and insonification.

Issue	Hearing Generalists	Hearing Specialists
Permanent Threshold Shift (PTS)	No data available	No data available
Temporary Threshold Shift (TTS)	No relevant data available	Smith et al. 2004a, b (goldfish; band-limited noise) Scholik and Yan 2001 (fathead minnow; band-limited white noise) Popper and Clarke 1976 (goldfish; pure tones)
Behavioral Changes	Wardle et al. 2001 (Exposed fish and invertebrates on reef to continuous air gun with no significant behavioral changes)	No data available
Eggs and Larvae	Banner and Hyatt 1973 (*Cyprinidon* and *Fundulus* showed somewhat decreased egg viability and larval growth in tanks with increased noise) Kostyuchenko 1973 (Increased egg mortality up to 20 m from seismic source) Booman et al. 1996 (Variable results with some stages showing decreased growth in a few species when exposed to air guns)	No data available
Miscellaneous	Skalski et al. 1992 (*Sebastes* catch decreased after one air gun blast) Engås et al. 1996 (Haddock and cod catch reduction after seismic survey blasts) Engås and Løkkeborg 2002 (Haddock and cod catch reduction area after seismic survey blast Slotte et al. 2004 (herring & blue whiting do not enter the area of air gun during use)	Smith et al. 2004a (no change in corticosteroid levels after continuous exposure to band limited noise)

Wardle et al. (2001) used a video system to examine the behaviors of fish and invertebrates on a coral reef in response to emissions from seismic air guns that were carefully calibrated and measured to have a peak level of 210 dB re 1 µPa at 16 m from the source and 195 dB re 1 µPa at 109 m from the source.. They found no permanent changes in the behavior of the fish or invertebrates on the reef throughout the course of the study, and no animals appeared to leave the reef. There was no indication of any observed damage to the animals..

Finally, Turnpenny et al. (1994) examined the behavior of three species of fish in a pool in response to different sounds, but results are not useable because of lack of calibration of the sound field at different frequencies and depths, and many other problems with experimental design (Ellison 1996). In enclosed chambers that have an interface with air, such as tanks and pools used by Turnpenny et al., the sound field is known to be very complex and will change significantly with frequency and depth.

While not totally germane to fishes, there is some evidence that an increased background noise (for up to three months) may affect at least some invertebrate species. Legardère (1982) demonstrated that sand shrimp (*Crangon crangon*) exposed in a sound proof room to noise that was about 30 dB above ambient for three months demonstrated decreases in both growth rate and reproductive rate. In addition, Legardère and Régnault (1980) showed changes in the physiology of the same species with increased noise, and that these changes continued for up to a month following the termination of the signal.

Indeed, we are now aware that fishes, as mammals and probably all other vertebrates, glean a great deal of information about their environment from the general sound field. In other words, whereas visual signals are very important and useful for things near the animal and in the line of sight, substantial information about the unseen part of an animal's world comes from acoustic signals.[9]

One may therefore think of fishes as using two "classes" of sound. The first is the well-known group of communication signals used to keep in touch with other members of a species and detect the presence of predator or nearby prey. The second are the sounds of the environment that, for a fish, might include the sounds produced by water moving over a coral head, waves breaking on shore, rain, and many more physical and biological sources. Bregman (1991) coined the term "Auditory Scene" to describe the acoustic environment. The acoustic environment has become of increasing importance in the overall understanding of hearing for all animals during the past 15 years. Moreover, it is becoming increasingly clear that one of the major roles of the auditory system is to discriminate between, and determine the position, of sounds in the auditory scene, using a mechanism called "stream segregation" (Bregman 1991; Fay and Popper 2000; Popper et al. 2003) whereby an organism is able to distinguish between two sounds ("streams") that differ in some way such as direction of the source, frequency spectrum, etc.

B. Stress – Physiological Responses

The impact of stress is much more difficult to define because it is hard to quantify this measure in fish since it has not been extensively studied; however, increased background noise is known to increase stress in humans (e.g., NIH/CDC 1990; von Gierke and Eldred 1993; Pearsons et al. 1995). There is evidence that the effects on non-auditory aspects of an animal's physiology, such as an increase in stress levels, can come from increased background noise or exposure to a sudden increase in sound pressure **(**e.g., Hattingh and Petty 1992). In turn, increased stress does impact overall human health and well-being, and it is reasonable to suggest that sound is also likely to cause stress in fishes. Thus, a considerable concern with regard to aquatic organisms (as to humans and other terrestrial organisms) not only related to the impact of exposure to sound on the function of the auditory receptor, but also to the impact of any sounds that are above ambient levels on overall health and well-being.

[9] Whereas terrestrial animals can also gain a good deal of information from chemical signals, such signals are less useful in water where there is a very high and rapid dilution factor. As a consequence, chemical signals are not as useful in water as in air, unless animals are very close to one another (e.g., within visual range) (Tavolga 1971).

An early study by Gilham and Baker (1984) used vibration of the aquarium walls to measure stress responses in rainbow trout. Although the stressors were not quantifiable, this study demonstrated that a general stress response occurred in fish between 1 and 5 days after signal onset, as demonstrated by significant increases in serum cortisol levels. Other studies have demonstrated that exposure to non-traumatic stressors (i.e., crowding, spawning, rapid environmental changes, suboptimal water quality or physical environment, altered conductivity, and pollution) can predispose fish to opportunistic infections (e.g., Walters and Plumb 1980; Noga et al. 1998; Wedemeyer 1999; Pickering 1981). Mesa (1994) found that salmonid smolts going over a hydroelectric dam had significant stress effects, and this made them more susceptible to predation than fish that had not gone over the dam. While the stimulus in this study was vastly different than just high-level sound, the results do suggest that if exposure to sound results in highly stressed fish, even if fish do not die as a direct result of stimulation, they may be more susceptible to predation or other environmental effects than non-stressed fish.

Smith et al. (2004a) demonstrated that corticosteroid levels do not change at a statistically significant level in response to exposure to high sound levels in goldfish (*Carassius auratus*). Corticosteroid level is a measure of stress, and suggests that stress levels in these animals were not influenced by continuous exposure to band limited noise in the 0.1 – 10 kHz frequency band with an overall rms pressure level of 170 dB re 1 µPa. While these results are of considerable interest, they provide only the first data in what must be a larger-scale examination of effects of sounds on stress levels in fishes. Indeed, Smith et al. (2004a) recommended additional studies on goldfish, and similar studies must be done on other species as well. One must be cautious, however, in extrapolating between species and between different experimental paradigms in trying to understand the effects of potential stressors on physiology.

C. Temporary and Permanent Hearing Loss

There are two classes of effects of exposure to sound on the ear. Exposure to low levels of sound for a relatively long period of time or exposure to higher levels of sound for shorter periods of time may result in temporary hearing loss, referred to as temporary threshold shift or TTS (e.g., Lonsbury-Martin et al. 1987). The level and duration of exposure that causes TTS varies widely and can be affected by factors such as repetition rate of the sound, pressure level, frequency, duration, health of the organisms, and many other factors. By definition, hearing recovers after TTS. The extent (how many dB of hearing loss) and duration of the TTS may continue from minutes to days after the end of exposure, and the extent of TTS depends on many variables.

The second possible effect is referred to in the literature as permanent threshold shift or PTS. PTS is a permanent loss of hearing and is generally accompanied by death of the sensory hair cells of the ear (e.g., Saunders et al. 1991).

Laboratory studies have been used to determine whether there may be temporary or permanent changes in hearing ability in animals exposed for short or long periods of time to different types of sound (e.g., pure tones or white noise). TTS has been found using behavioral or physiological tests for several fish species, including goldfish (*Carassius auratus*) and fathead

minnows (*Pimephales promelas*) (e.g., Popper and Clarke 1976; Scholik and Yan 2001, 2002; Smith et al. 2004a, b).[10]

In a recent set of studies, Smith et al. (2004a, b) tested hearing in goldfish and tilapia (*Oreochromis niloticus*) to determine more detailed parameters of hearing loss, including the effects of different exposure durations and recovery times. They demonstrated that goldfish had a 5-dB temporary threshold shift after only 10 minutes of exposure to band-limited noise (0.1 to 10 kHz, approximately 170 dB re 1 µPa overall spectral sound pressure level), and that goldfish with a three-week exposure to the same stimulus experienced a 28-dB threshold shift and took over two weeks to return to normal hearing. Similarly, Scholik and Yan (2001) demonstrated that fathead minnows did not recover to control thresholds even as long as 14 days after termination of a 24-hour exposure to white noise from 0.3 to 2.0 kHz with an overall spectral sound pressure level of 142 dB re 1 µPa.[11]

Both Smith et al. (2004a) and Scholik and Yan (2002) reported no TTS in two species of hearing generalists (tilapia and bluegill sunfish, *Lepomis macrochirus*).. In their experiments, however, the sound stimulus consisted of only pressure, whereas primarily the acoustic particle velocity in a sound field stimulates hearing generalists. Moreover, these researchers controlled only the sound pressure level during ABR measurements to determine the audiograms before and after sound. Thus these results are not relevant because hearing sensitivity and temporary threshold shifts in hearing generalists are meaningful only in terms of acoustic particle velocity or acoustic intensity. It is unlikely that TTS would be found in a hearing generalists exposed only to sound pressure.

Two recent investigations used exposure to high-level anthropogenic sources to test hearing loss and effects on other aspects of fish biology. In one study, Popper et al. (in prep. a) used a U. S. Navy SURTASS low frequency active (LFA) sonar transducer and tested hearing in the rainbow trout (*Oncorhynchus mykiss*), a salmonid of the same genus as many endangered Pacific Coast salmon, and channel catfish (*Ictalurus punctatus*) (to represent hearing specialists). They found that exposure to three emissions of the sonar, each for 108 seconds (with nine minutes between signals) with a received sound level at the fish of 193 dB re 1 µPa (rms) (frequency bandwidth about 160-325 Hz), produced up to 10 dB of temporary threshold shift. Preliminary evidence suggests that the fish recovered from this TTS within 24-48 hours. Moreover, there was no mortality to fish exposed to the SURTASS LFA source, even up to four days (96-hours) post-exposure. Preliminary results from necropsy and histopathology on experimental and control animals showed no damage to other organ systems, including the ear.

[10] It is important to note that the sound levels expressed in these TTS studies were done based on sound pressure level, but should more correctly be determined in terms of cumulative energy exposure. Future experiments need to be done in such context to allow comparison between studies, animal groups, and, most importantly, different signal parameters (e.g., bandwidth, duration, temporal variation). The importance of the studies cited here lie with the observations that TTS does take place in fish, and that the effects of TTS may last for a considerable time after the termination of the sound source.

[11] It must be noted that it is unclear in this study if the units on the sound pressure level were reported correctly. For band limited white noise, the correct units for spectral density level are $\mu Pa^2/Hz$ and one has to multiple by the total bandwidth to get the overall sound pressure level. A spectral density level of 142 dB over a bandwidth of 1700 Hz would have an overall sound pressure level of 174 dB (re 1 µPa), which is on par with the level found to cause TTS in goldfish, another hearing specialist, by Smith et al. (2004a,b). This study needs to be duplicated to confirm that TTS occurs in fathead minnows when exposed to white noise at such a low sound pressure level.

In the second study, Popper et al. (in prep. b) tested three species, including another salmonid (broad whitefish, *Coregonus nasus*), after stimulation with five blasts of a seismic air gun with a received mean peak sound level of about 205 dB re 1 μPa (a received mean SEL of about 175 dB re 1 μPa^2-s). The broad whitefish showed no TTS to this signal, whereas northern pike (*Esox lucius*) (a hearing generalist) and lake chub (*Couesius plumbeus*) (a hearing specialist) showed 10-15 dB of hearing loss and complete recovery within 24 hours after exposure.

While extrapolation between these results and exposure to sound produced by pile driving, or between these species and most Pacific Coast species, must be done with considerable caution, they do suggest that limited exposure to high-level sounds of some types does not result in death, and that any hearing loss is likely temporary.

In humans and other terrestrial vertebrates, exposure to extremely high sound pressure levels, for even a short period of time, may result in permanent hearing loss. This occurs because the sound mechanically destroys the sensory hair cells of the inner ear and/or fractures or dislocates the ossicular chain of the middle ear (Roberto et al. 1989; Patterson and Hamernik 1997). It is significant that exposure to sound at lower levels, but for longer periods, as in a noisy work environment, can also lead to permanent hearing loss through death of sensory cells (Kryter 1985; Hamernik et al. 1994). At the same time, the data on the effects of exposure to these types of sounds on fishes are very limited as compared to data for terrestrial vertebrates; but, there is a small body of peer-reviewed literature showing that such exposures to sound can destroy the sensory cells in fish ears (Enger 1981; Hastings et al. 1996; McCauley et al. 2003). No study, however, has yet examined the relationship between destruction of hair cells and permanent hearing loss in fishes.

While looking for evidence of frequency discrimination in the ears of Atlantic codfish (*Gadus morhua*), Enger (1981) found that some sensory cells lost their ciliary bundles (and were potentially destroyed) after one- to five-hours exposure to pure tones at frequencies from 50 to 400 Hz with a sound pressure level of 180 dB re 1 μPa (rms) This is 100-110 dB above threshold in the most sensitive hearing frequency range for codfish. Enger used a waveguide instrumented with a sound projector at each end to produce an exposure that had negligible particle velocity.

In a similar study, Hastings (1995) reported damage to auditory hair cells in goldfish (*Carassius auratus*) exposed to continuous tones having levels of 189, 192, and 204 dB re 1 μPa (peak) at 250 Hz and 197 dB re 1 μPa (peak) at 500 Hz for approximately two hours. These sound pressure levels are at least 120-140 dB above auditory thresholds for goldfish at these frequencies. This study also used a waveguide that allowed exposure to sound with negligible particle velocity. Four fish were exposed at each set of conditions, and damage was found to correlate with sound pressure level at a 95% confidence level. This study also included several controls (fish placed in the waveguide and held for 2 hours, but not exposed to sound). In addition, goldfish exposed to 182 dB re 1 μPa (peak) at 500 Hz had no hair cell damage. This is approximately 120 dB above auditory threshold at a frequency in the most sensitive range.

Hastings et al. (1996) demonstrated similar effects on the ears of the oscar (*Astronotus ocellatus*). Sensory cells in the ears of four out of five animals were damaged after one hour of continuous exposure to a 300-Hz pure tone at 180 dB re 1 μPa (peak), while no damage occurred

after one-hour exposure to the same tone applied for 20% of each minute. It is important to note that damage was not evident in animals after one day, but was evident in the animals that were kept alive for four days following exposure. These results suggest that damage from exposure to sound takes some time to become visually apparent. The particle velocity in the waveguide used by Hastings et al. (1996) was about one-fifth that which would be associated with the same acoustic pressure in open water; however, because the stimulus was a plane wave, the average acoustic intensity for these exposures, 1.67 J/m^2-s, can be calculated. This gives an estimated total average acoustic energy exposure of 6000 J/ m^2 (after one hour) for hair cell damage, and 1200 J/ m^2 resulting in no hair cell damage.

McCauley et al. (2003) investigated the effects of exposure to the sounds of a seismic air gun on the Australian fish, the pink snapper (*Pagrus auratus*). Fish were in a cage and exposed to several air gun emissions at different distances. The animals were kept alive for different time intervals after exposure. After the animals were sacrificed, their ears were examined for signs of damage using electron microscopic techniques very similar to those used by Hastings et al. (1996). The results clearly showed extensive damage to the sensory hair cells of the ear in several of the animals. The extent of damage increased with the post-exposure period up to at least 58 days (the maximum survival interval described).

While the McCauley et al. (2003) study further substantiated the potential for destruction of hair cells in fish when exposed to high level sounds, both the McCauley et al. (2003) and Hastings et al. (1996) studies were careful to provide a number of important caveats to their work. These included (a) use of only a few species, which may not be representative of other species; (b) the inability of the caged fish to escape from the sound field; and (c) the relatively long duration of exposure as compared to exposures to what would be expected from other types of human-generated sounds of that sound pressure level.

One difference between these studies that needs to be controlled in future investigations is the relationship between acoustic pressure and particle velocity in the sound stimulus. While it was possible for Hastings et al. (1996) to calibrate both pressure and particle velocity in their test chamber, this was not done by McCauley et al. (2003). The importance of having full characterization of the stimulus in these and future studies is to enable correlation of results with the specific component(s) of the sound stimulus and thus comparison of results between studies.

It again needs to be pointed out that hair cell damage observed in these four species (codfish, goldfish, oscar, pink snapper) was only a visual manifestation of what may have been a much greater effect, and that observable physical evidence took days to show up. It may be more important to evaluate the more immediate effects of the sounds on hearing capabilities of the fish, as was done by Popper et al. (in prep. a, b). Even if there is only TTS as a result of a loud sound, temporary deafness could result in a fish being unable to respond to other environmental sounds that indicate the presence of predators and facilitate the location of prey and mates. Effects, however, depend on the use of sound by that species in those situations.

While it is clear from the data discussed above that sounds of some types over time can affect the ear and hearing, it is important to note that at this stage of our knowledge, and the very limited data, that one must be extremely cautious in extrapolating results between species or received signals. Thus, results for one species may not be indicative of the results one would

obtain for another species using the same type of signal, and the results from one type of signal (e.g., air gun) may not be germane to another signal (e.g., pile driving).

The reasons for not being able to extrapolate results are many and include: (a) differences in the hearing systems of different fish species and too little knowledge about the effects of exposure to sound on such different auditory systems; (b) limited data on the precise nature of a stimulus (e.g., pressure and/or particle velocity) which might affect the hearing apparatus; and (c) the time course (e.g., continuous vs. transient) and frequency components of different signals. To be able to reasonably extrapolate between species and signals, much more will need to be known about the effects of sounds on different auditory systems.

Furthermore, it will be imperative to have common ways of expressing exposure to sound so that it is possible to compare stimulus parameters between signals of different types, especially for impact and impulse sounds. Indeed, several studies on guinea pigs and chinchillas have shown that the L_{eq} and SEL metrics do not correlate with TTS and PTS when the stimulus includes impulsive or transient sounds. Lataye and Campo (1996) found that L_{eq} was not an accurate predictor of noise-induced hearing loss (NIHL) in guinea pigs when the temporal characteristics of the sound were varied. Their results indicate the existence of a "critical intensity" as a demarcation between metabolic and mechanical damage mechanisms, which is not accounted for in the time-averaged L_{eq}. Hamernik et al. (1974) showed that when continuous and impulse noises were combined, chinchillas experienced higher levels of TTS and hair cell damage than the additive effects of either component. In more recent studies, Hamernik and Qiu (2001) also found that NIHL did not correlate with L_{eq} in chinchillas when the sound exposure included impact signals mixed with band-limited noise even though all exposures had the same total energy.

Both Hamernik and Qui (2001) and Hamernik et al. (2003) reported that the kurtosis metric (a statistical measure used to estimate the deviation of the signal amplitude distribution from a normal distribution) correlated with TTS, PTS and outer hair cell loss for exposures that contained high-level transients (impacts or noise bursts). They found no correlation with energy metrics. Given the results of these studies, it is premature to provide any guidance on exposure levels that could cause TTS or PTS in any fish species based on research reporting TTS when exposed only to pure tones or white noise signals.

Finally, it should be noted that the same concerns regarding stimulus parameters and extrapolation between species applies to all other aspects of the effects of exposure to sound on fishes (or any animal, for that matter). Some of these other effects are discussed below.

D. Structural and Cellular Damage of Auditory and Non-Auditory Tissues

Compared to data for the effects of exposure to sound on fish hearing capabilities and the ear, there are even fewer peer-reviewed data regarding the effects on other aspects of fish biology. Little work has been done to determine the non-auditory effects of sound on fish. It is widely known that exposure to sounds at high levels can alter the physiology and structure of terrestrial vertebrates (e.g., Fletcher and Busnel 1978; Saunders et al. 1991). Indeed, there are strong standards set by the Occupational Safety and Health Administration (OSHA) recognizing

that high levels of background sound have an impact on human well-being (e.g., NIH 1990; von Gierke and Eldred 1993; Pearsons et al. 1995). These changes may include cellular changes, organ system changes, or stress level effects caused by exposure to sound. Exposure to sound at ultrasonic frequencies (~ 750 kHz and higher) have even induced cardiac arrhythmias in humans and premature ventricular contractions in frogs (Dalecki et al. 1991); however, these effects have not been observed at lower frequencies that characterize the sound produced by pile driving.

While there are far fewer data on the impact of exposure to sound on the health and well-being of laboratory animals, and far less known about the impact of exposure on wild animals (including aquatic animals), it is reasonable to suggest that long-term exposure to relatively high levels of sound could impact all vertebrates (e.g., Richardson et al. 1995) (just as does shorter term exposure to higher level signals). For example, one of the organ systems of most concern with marine mammals is the lungs, and the resultant damage that may occur in this organ due to the presence of air. Most fishes do have at least one large air chamber, the swim bladder, which provides the same discontinuity between water and air as does the lung in marine mammals.

Studies on terrestrial mammals have indicated that gas-filled structures (i.e., lung) or gas pockets (such as could occur in the gastrointestinal tract) within a body make it susceptible to damage by sound (Richmond et al. 1973; Fletcher et al. 1976; Yang et al. 1996; Bauman et al. 1997; Dodd et al. 1997; Elsayed 1997). Tissue damage can occur when sound passes through the interface from a fluid tissue structure (e.g., adipose tissue and muscle) to a gas void because the gas is more compressible then the fluid, resulting in a relatively large increase in the motion of the connective tissue between the two. In addition, sound will cause gas organs such as the swim bladder and lung to oscillate and push on the surrounding tissues. The amplitude of these oscillations can be quite large at high sound pressure levels or even at lower sound pressure levels if the gas organ is excited at its resonance frequency.

In fishes, gas oscillations induced by high sound pressure levels can even cause the swim bladder to tear or rupture, as has been indicated in response to explosive stimuli in several gray literature reports (e.g., Alpin 1947; Coker and Hollis 1950; Gaspin 1975; Yelverton et al. 1975). While similar results have been observed in fish exposed to pile driving sound (Caltrans 2001, 2004; Abbott and Bing-Sawyer 2002), there was no swim bladder damage in response to exposure to SURTASS LFA sonar (received level of 193 dB rms re 1 μPa) or seismic air guns in two recent studies (Popper et al. in prep. a, b). Both of these sources produce transient sounds having approximately the same frequency bandwidth as pile-driving signals.

It has been suggested that the large negative overpressure characteristic of pile driving sounds may be more damaging to the swim bladder than the initial positive overpressure (Trasky 1976; Caltrans 2004) because of its relatively large expansion during the negative phase. Bailey et al. (1996), however, found that a sound pulse having a large positive peak overpressure was at least as damaging as one having a large negative peak overpressure of approximately the same level and time duration, to the lungs of mice submerged in water. Damage increased with magnitude of pressure incident at the lung, but histology showed no qualitative or quantitative differences between the effects of positive and negative pressures. Mouse lungs had increasing hemorrhage with increasing exposure levels regardless of the polarity of the peak overpressure. These findings indicate that injury would correlate with the work done on the lung tissue, which would be equivalent to the total energy in the sound wave.

Although it is possible to electronically invert pressure waveforms when they are recorded because of the characteristics of the instrumentation and potentially misinterpret the results of such tests, Bailey et al. (1996) created a sound pulse having a large negative peak overpressure by reflecting the pulse with positive peak overpressure from the interface between water and air at the top of their test tank. The sound pressure reflection coefficient at this interface is –1. Therefore, because they used a signal and its reflection from the water surface and found no difference in damage based on polarity of peak overpressure, they obtained legitimate results even if their recording instrumentation happened to invert the pressure waveforms.

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Govani et al. (2003) also concluded that the total energy in the sound wave, regardless of pressure polarity, was responsible for observed effects of submarine detonations on juvenile pinfish (*Leiostomus xanthurus*). Moreover, Stuhmiller et al. (1996) concluded that incidence of blast injury to the lung and lethality correlates with total energy in the wave normalized by lung volume in terrestrial animals. Their results were so strong that they recommended that potential for blast injury to the lung could be determined from this simple model without additional animal testing.

Other structures within the body can be affected by exposure to sound because of their small size or dynamic characteristics. There is some evidence to suggest that sound at sufficiently high-pressure levels can generate bubbles from micronuclei in the blood and other tissues such as fat (ter Haar et al. 1982). In fish, blood vessels are particularly small in diameter so bubble growth by rectified diffusion (Crum and Mao 1996) at low frequencies could create an embolism and burst small capillaries to cause superficial bleeding. This type of bubble growth may also occur in the eyes of fish where the tissue might have high levels of gas saturation (see non peer-reviewed reports by Turnpenny et al. 1994; Gisiner 1998).

Another type of tissue damage caused by exposure to high-level, transient sound is traumatic brain injury (TBI) or neurotrauma. In humans, TBI can occur with no marks of external injury, but manifests itself with instantaneous loss of consciousness or sustained feelings of anxiety and confusion, or amnesia, and may result in death (Elsayed 1997; Knudsen and Oen 2003). The underlying physical mechanisms for these manifestations are cerebral edema, contusions and lacerations, as well as hemorrhages in the meninges (protective tissues around the brain), brain substance, nerve roots, and ventricles (fluid-filled spaces within the brain and spinal cord) that may result from extreme relative motion between the skull and brain during exposure to high overpressures. Hastings (1990, 1995) reported “acoustic stunning” in four blue gouramis (*Trichogaster trichopterus*) exposed for approximately eight minutes to a 150-Hz pure tone with a peak pressure of 198 dB re 1 μPa. Three out of four of these fish recovered. The loss of consciousness exhibited by these fish could have been caused by neurotrauma, especially since this species has a bubble of air in the mouth cavity located near the brain that enhances hearing capability of this species (Yan 1998; Ladich and Popper 2004). Thus fish with swim bladder projections or other air bubbles near the ear (e.g., butterfly fish, squirrel fish, and many other species) could be susceptible to neurotrauma when exposed to high sound pressure levels.

Elsayed (1997) conducted a series of investigations using terrestrial animal models to examine biochemical responses in tissues to blasts. He and his colleagues have found two

responses that correlate with blast overpressure: (1) depletion of antioxidants and (2) lipid pre-oxidation. Cernak et al. (1996) also examined biochemistry related to neurotrauma in blast injury. They also found lipid pre-oxidation products as well as increased levels of lactate and calcium ions and decreased levels of glucose and magnesium and zinc ions. Changes in lactate and glucose levels indicate changes in metabolism and energy in the damaged tissue, while changes in ion concentrations indicate cellular disruption and damage. Cernak et al. (1996) postulate that afferent neural signals from injured organs (such as lungs) could impair central nervous system (CNS) function and contribute to further damage over time. The biochemical mechanisms of acoustic traumas and barotraumas, as well as their acoustic thresholds, however, remain undefined.

Studies reported by several investigators (e.g., Hastings 1990, 1995; Turnpenny et al. 1994; Caltrans 2001, 2004; Abbott and Bing-Sawyer 2002) also describe non-auditory damage to fish caused by sound including evidence of capillary rupture in the skin, neurotrauma, eye hemorrhage, swim bladder rupture, and death. Hastings showed that pond-size goldfish could not survive 2-hour continuous wave exposures at 250 Hz and a sound pressure level of 204 dB re 1 μPa (peak), and blue gouramis could not survive 0.5-hour continuous wave exposures at 150 Hz and 198 dB re 1 μPa (peak).

The work by Turnpenny et al. (1994) resulted in the investigators suggesting significant damage to caged fishes resulting from exposure to sound. They reported mortalities 24 hours post-exposure in brown trout and whiting after exposure for only five minutes to various tones at levels as low as 170 dB (re 1 μPa) (assumed to be rms, but not reported as such) at frequencies from 95 to 410 Hz. However, this non-peer-reviewed study has significant problems with the experimental design, acoustic environment, data analysis, and poor (or non-existent) controls. The acoustic design of the test chamber (a 30 cm x 30 cm x 30 cm mesh cube ensonified by four different sound projectors and located near the water surface) was such that the sound pressure level could not be controlled as indicated in the report (see Ellison 1996). Indeed, no other studies have reported any physical damage or mortality in fishes after exposure to this low of a sound pressure level for only five minutes. Sound pressure is zero at a water surface, so it is likely that there was significant mechanical energy not taken into account in the test chamber because of severe pressure gradients that created oscillatory fluid motion.

At the same time there are very few studies known to have involved a professional fish pathologist to do full necropsy and histopathology after noise exposure (Popper et al. in prep. a; Marty 2004). Popper et al. (in prep. a) showed that there were virtually no effects on any body system in rainbow trout and channel catfish as a result of exposure to SURTASS LFA sonar at received levels of 193 dB re 1μPa (rms). Marty (2004) examined fish following their exposure to four minutes of driving of concrete piles at the Port of Oakland. While Marty found some pathology, it did not differ between sound-exposed and control groups, suggesting that any pathology may have been from prior effects or disease. Indeed, these results highlight the necessity of involving a professional fish pathologist in studies of this type because it is exceedingly easy to impose artifacts in the tissue as a result of mishandling or poor tissue preparation.

Significantly, the studies by Hastings (1990, 1995), Turnpenny et al. (1994), Caltrans (2001), Abbott and Bing-Sawyer (2002) and Caltrans (2004) do not appear to have involved a

professional fish pathologist. In addition, Abbott and Bing-Sawyer (2002) sacrificed fish by putting them in plastic bags and placing them on ice, whereas Caltrans (2004) sacrificed fishes in other ways but then froze the animals. While differences were reported between exposed and control animals in pile driving studies (though one study (Caltrans 2001) showed damage in 70% of controls that were attributed to handling), it is possible that handling post stress from exposure to sound resulted in the reported pathology, rather than being caused directly by exposure to pile driving signal per se. Moreover, it is widely known that freezing damages tissues and cells and such damage could make recognizing actual effects of exposure to sound exposure difficult because it would "mask" effects of sound exposure in both experimental and control animals.[12]

1. *Juvenile and Adult Fish*

Key variables that appear to control the physical interaction of sound with fishes include the size of the fish relative to the wavelength of sound, mass of the fish, anatomical variation, and location of the fish in the water column relative to the sound source. Yelverton et al. (1975), in an important and well-conducted study reported in the gray literature, provides the most definitive study of the gross effects of sound generated by underwater blasts on fishes.

Explosive blast pressure waves consist of an extremely high peak pressure (called overpressure) with very rapid rise times (< 1 ms). Yelverton et al. (1975) exposed eight different species of fish, five with ducted swim bladders (physostomes) and three with non-ducted swim bladders (physoclists – see glossary, page 61) to blasts. The physostomes were top minnow (*Gambusia affinis*), goldfish (*Carassius auratus*), carp (*Cyprinus carpio*), rainbow trout (*Salmo gairdneri* [now *Onchorhyncus mykiss*]), and channel catfish (*Ictalurus punctatus*), and the physoclists were guppy (*Lebistes reticulates*), bluegill (*Lepomis macrochirus*), and large mouth bass (*Micropterus salmoides*). The test specimens ranged from 0.02 g (guppy fry) to 744 g body mass (large carp) and included small and large animals from each species. The fish were exposed to blasts having extremely high peak overpressures with varying impulse lengths. Yelverton et al. (1975) found a direct correlation between body mass and the magnitude of the "impulse," characterized by the product of peak overpressure and the time it took the overpressure to rise and fall back to zero (units in psi-ms), which caused 50% mortality as shown in Figure 7 (page 67). Trasky (1976) also reported significant differences between adult fishes, and salmon and herring fry in the lethal blast overpressure from buried seismic charges

Similar to the findings of Stuhmiller et al. (1996) for blast injury to lung and lethality in terrestrial animals, the results of Yelverton et al. (1975) indicate that a metric related to the amount of sound energy received, such as the sound exposure level or integral over time of the acoustic intensity, rather than just peak pressure correlates with swim bladder and other tissue damage as well as mortality in fish. In fact Yelverton et al. (1975) concluded that peak pressure alone did not correlate with damage because peak pressure was kept constant and the impulse duration was varied or vice versa in their study. The injuries they observed included swim bladder rupture, kidney damage, and liver damage. While these data are important, there is concern regarding the experimental design used by Yelverton et al. (1975). The primary concern

[12] A much more effective, and accepted, method of preservation for necropsy is to place the tissue into buffered formalin.

is a lack of controls to evaluate fish handling procedures. Without these controls there is an issue in quantifying damage to fish strictly attributable to exposure to the explosions compared to damage attributable to handling.

Additional studies, primarily in the gray literature, using explosives suggest that there is far more damage to fishes with swim bladders than to species, such as flatfish, that do not have such air chambers (e.g., Coker and Hollis 1952; Gaspin 1975; Baxter et al. 1982; Goertner 1994). It has also been shown that the effects on fish decline rapidly with distance from the explosion (e.g., Houghton and Mundy 1987; Goertner 1994) as the peak overpressure decreases and the impulse duration increases. Similarly, a study by Kearns and Boyd (1965) suggested that the extent of fish kill decreases with increasing distance of the fish from an air gun source, and another unpublished study indicated no mortality from seismic air gun shots at considerable distance (4000 m) from the source (Thomsen 2002). There is evidence that the effects of explosions vary by species, even when all test fish have a swim bladder (Govoni et al. 2003). Based on these and other studies (e.g., Yelverton et al. 1975), it is clear that there is considerable variability in the effects of explosive blasts on fishes, and that the variables include received sound energy, presence or absence of gas bubbles (e.g., swim bladder), mass of fish and perhaps body shape (e.g., Teleki and Chamberlin 1978), and biomechanical properties of the swim bladder wall.

2. *Eggs and Larvae*

In considering fishes, it is important to not only think in terms of adults, but also in terms of fish eggs and larvae. Whereas it is possible that some (though not all) species of fish would swim away from a sound source, thereby decreasing exposure to sound, larvae and eggs are often at the mercy of currents and move very slowly, if at all. Eggs are often stationary and thus could be exposed to extensive human-generated sound if it is presented in the area, including sound transmitted through water (i.e., eggs within the water column) or substrate (e.g., eggs deposited within substrate, such as salmonid redds).

Data on effects of sound on developing eggs and larvae are very limited. There is some suggestion in the literature that developing larvae have different levels of sensitivity to mechanical stimulation at different stages of development (e.g., Piper et al., 1982; Jensen and Alderice 1983, 1989; Dweyer et al. 1993). However, virtually all these studies used explosions or large mechanical shocks. For example, Jensen and Alderice (1989) (also see Jensen and Alderdice 1983) did controlled drops of trays of five salmonid species and rainbow trout from different heights and then examined for mortality over time (e.g., Jensen and Alderice 1989). In this study, Jensen and Alderice found that there was greatest mortality to eggs dropped before they had started to divide (activation), whereas other investigators found no effects. Post et al. (1974) dropped rainbow trout eggs in a way designed to mimic the effects of the seismic effects of near-by nuclear blasts and found no effects on eggs of any ages, whereas Smirnov (1959) mechanically agitated salmon eggs (no description of this agitation was provided other than that it was a mechanical stimulus of some sort) and found different levels of mortality at different ages post the start of cell division.

Banner and Hyatt (1973) conducted the only peer-reviewed study on the effect of sound on eggs and development in fish, and it was never followed up with additional investigations. They found an increased mortality of eggs of and embryos of *Cyprinodon variegates* exposed in 20-litre glass aquaria to broadband noise (100-1,000 Hz) that was about 15 dB above ambient sound level. The sound did not affect hatched fry of *C. variegates*, and neither eggs nor fry of *Fundulus similes* were affected. Banner and Hyatt (1973) also found that the larval growth was significantly less in the noise-exposed larvae of both species than in the larvae raised in ambient noise. (Interestingly, these findings parallel studies showing that shrimp exposed to noise have slower growth than controls not exposed to noise [Legardère 1982].) While these results are of considerable interest, they were from only two species subject to relatively low noise levels and for a limited time period.

Indeed, there are several issues that must be considered with regard to the effects on eggs and larvae of exposure to sound. These include: (a) immediate effects as measured by mortality; (b) long term effects, even after the termination of the insonification, as measured by mortality; (c) long term effects from which recovery is possible if the fish is not subject to predation or other factors that kill it during the recovery time; (d) effects on egg development and viability, (e) effects on short and long-term growth of the developing larvae and young fish in the presence of sound and/or after termination of sound; (f) effects of exposure to sound on the development and function of various organ systems; and (g) potential differences in effects at different stages of development.

Several other sets of data are worth noting. A non peer-reviewed study on the effects of sounds from 115-140 dB (re 1 µPa, peak[13]) on eggs and embryos in Lake Pend Oreille (Idaho) reported normal survival or hatching (Bennett et al. 1994). However, few data were provided that could be used to evaluate the results. In contrast, Kostyuchenko (1973) worked with marine fishes, none of which are related to the species on the Pacific Coast, to determine the effects of seismic air gun sounds on eggs. Kostyuchenko reported damage to eggs at up to 20 m from the source. Similarly, a Norwegian group (Booman et al. 1996) investigated the effects of seismic air guns on eggs, larvae, and fry and found significant mortality in several different marine species (Atlantic cod, saithe, herring) at a variety of ages, but only when the specimens were within about 5 m of the source, and the most substantial effects were to fish that were within 1.4 m of the source. These authors also reported damage to neuromasts (sensory structures with sensory hair cells) of the lateral line system and to other organ systems; however, data are limited to just a few species and need replication. At such close distances to the air gun array, the particle velocity (i.e., oscillatory fluid motion) would be huge, but the received sound pressure and particle velocity were not measured in this study.

There are a number of other gray literature studies of the effects of sound on developing eggs and larvae; none provide conclusive evidence on this topic that is germane to most Pacific Coast species. Indeed, one can conclude that there is a total dearth of material on this topic and it is an area of research that needs rigorous experimental evaluation.

[13] On page 29 of this report the authors report measuring peak sound levels for one part of the study, but no where else is there any indication that sound levels were peak or rms.

In summary, the few studies on the effects on eggs, larvae, and fry are insufficient to reach any conclusions with respect to the way sound would affect survival. Moreover, most of the studies were done with seismic air guns or mechanical shock and these are stimuli that are very different than those produced by pile driving. The results suggesting some damage and death need to be followed up in a way that would be relevant to pile driving and the characteristic sound transmitted through water and substrate.

3. *Lateral Line*

The lateral line system consists of a set of receptors found on the surface of the body in all fishes (Dijkgraaf 1963; Coombs and Montgomery 1999) that detect water motion within a few body lengths of the fish (e.g., Denton and Gray 1989). The sensitivity of the lateral line system is generally below a few hundred Hertz, and there appears to be a dichotomy of function between lateral line receptors that lie below the surface of the skin in canals and those that lie on the surface of the body (e.g., Montgomery et al. 1997). The major sensory unit of the lateral line is the same mechanosensory hair cell found in the ear of all vertebrates. In the lateral line, the ciliary bundle projects into a gelatinous structure (the cupula) that bends or is displaced in response to hydrodynamic stimulation, thereby causing bending of the ciliary bundles of the sensory hair cells (Coombs and Montgomery 1999).

The only study on the effect of exposure to sound on the lateral line system suggests no effect on these sensory cells (Hastings et al. 1996). While not directly relevant to potential effects due to sound, Denton and Gray (1993) showed that mechanical stimulation of the lateral line of clupeids may cause damage by decoupling the cupulae from the neuromasts. Loss of the attachment between the cupula and neuromast would result in dysfunction of the lateral line. In their study, Denton and Gray did not consider the hair cells themselves, nor did Hastings et al. (1996) look at any effects on coupling of the cupula. The work from Denton and Gray (1993) suggest, however, that future studies of the lateral line should consider the coupling issue because damage to the coupling would have a significant effect on the function of the lateral line, just as would damage to the sensory cells themselves. This is reinforced by the very limited work on the lateral line by Booman et al. (1996).

E. Effects of Pile Driving on Fishes

As discussed in many places in this report, the data on the effects of pile driving on fishes are limited, and the results are equivocal. There is clearly evidence from reports in the gray literature that pile driving can potentially kill fishes of several different species if they are sufficiently close to the source (e.g., Abbott and Bing-Sawyer 2002; Caltrans 2004), although these same studies, as well as other investigations (e.g., Nedwell et al. 2003; Abbott 2004) suggest that fishes further from the source are not likely to be killed. While not testing fishes close to pile driving, the observation that fishes are not killed at a distance is supported by findings from Nedwell et al. (2003) who showed, in very limited and poorly reported studies, that fishes 400 m from a source, where the estimated received peak level was only 134 dB (re 1 µPa), were not killed by pile driving. While there are not specific data demonstrating that mitigating devices decrease mortality, this is certainly suggested based upon very limited data by

Caltrans (2004) showing that pile driving signals are significantly reduced in amplitude by devices such as air curtains.

Several studies have attempted to quantify non-mortality injuries that resulted from pile driving (e.g., Caltrans 2001, 2004; Abbott and Bing-Sawyer 2002; Abbott 2004; Marty 2004). While the ways for expressing the degrees of damage determined by most of these studies are long-standing (and based on early work by the great ichthyologist Carl Hubbs on the effects of explosives on fishes – e.g., Hubbs and Rechnitzer 1952), they are not readily quantifiable and quite gross in their expression of effects on fishes. Moreover, in all but one study (Marty 2004), pathology was done on fish that did not receive appropriate pathological or histological preparation or analysis (e.g., Kane 1996; Kane et al. 2000; Marty 2004).

For example, in the Caltrans (2001) and Abbott and Bing-Sawyer (2002) studies fishes were killed by being placed in plastic bags and then put on ice. The fish were then held for a period of time before analysis. This could have resulted in tissue degradation caused by the slow death of the fish, or from tissue breakdown, that may have "masked" any effects from the pile driving itself. While these studies report differences between exposed and control animals, controls were not treated precisely the same as experimental animals (e.g., controls placed in the water were only left in place for 10 – 15 minutes, vs. up to 30 minutes for exposed animals) and so it is not clear whether the differences were related to the pile driving or to the treatment. In contrast, a recent pile driving study for the Port of Oakland, using appropriate controls (Abbott 2004) and tissue preparation and histopathology on fish exposed in cages to pile driving 32-feet away showed no differenences in effects on tissues between sound-exposed and control animals (Marty 2004).

Other unpublished reports have attempted to observe the behavior of fish during pile driving activities (e.g., Feist and Anderson 1992; Bonar 1995). Feist and Anderson (1992), studying fish behavior at Everett Hopeport (Washington), found that there were more fish schools in an area when there was no pile driving activity then when there was pile driving activity. None of these studies reported any other notable effects on the fish or their behavior. At the same time, these observations were basically opportunistic observations of free-swimming fish rather than on animals with known received sound exposures related to pile driving activity. Thus, the results are not quantitative and need to be repeated in some quantitative fashion that allows investigators to relate behavior with known sound levels, distances from sources, etc. And, the studies need to observe the three-dimensional behavior of fishes rather than just behavior of fish at or close to the surface.

It is important to note that there are no studies that have examined longer-term effects of exposure to pile driving sounds that may lead to delayed death or, perhaps, to other alteration in behavior that could affect the survival of individuals or of populations of fishes. Nor have studies examined the non-mortality responses of fishes outside of the "kill-zone" that, while not immediately apparent, may have significant effects on fish populations. Non-mortality effects may include temporary injury that heals, injury that leads to a slow death (e.g., break down of tissues in some organ system), temporary or permanent hearing loss, movement of fish away from feeding grounds due to high signal levels, and many other possible scenarios. Thus, future investigations must not only examine immediate mortality of pile driving exposure on fish, but

they must also consider longer term effects on physiology and behavior, as well as effects on fishes that are at some distance from the source.

Finally, it is also important to consider the effects of cumulative exposures on mortality, physiology, and behavior. One such issue includes the effects of exposure to multiple impacts from pile driving and their intermittency (e.g., one every few seconds to several per second). One issue in this regard is whether there are any physiological differences when an animal is exposed to a very frequent sequence of high-level sound exposures vs. there being some "recovery" time between exposures. Another aspect of cumulative exposure that needs consideration may occur if a fish is in an area and exposed to pile driving, and then exposed again several hours, days, or weeks later. There are no data on whether any effects of earlier exposure will "heal" before the next exposure, or whether multiple exposures even over a long period of time without exposure leads to cumulative effects.

V. Areas of Uncertainty and Studies Needed

A number of questions need to be asked relevant to the effects of sound generated by pile driving. Three areas of study and evaluation include definition of interim guidelines on hearing thresholds for fish protection from sound generated by pile driving using the currently available data, studies to provide a clear characterization of pile driving sound, and studies to provide a more succinct description of fish injuries resulting from pile driving sound. To make these studies useful, they need to be done in a very highly specified sound paradigm and with species that are appropriate for study on the Pacific Coast (Table 2, page 17).

A. Guidance for Protection of Fish from Exposure to Pile Driving Sound

There are few experimental data available about the general effects of exposure to sound on fish species of the Pacific Coast, and the information available is possibly of little relevance to effects of pile driving sound because the studies were done using signals that are very different than those produced during pile driving. At the same time, there are some data showing that pile driving has the potential to directly kill fish and damage various organs and/or tissues when the animals are close to the source (e.g., Caltrans 2001, 2004; Abbott and Bing-Sawyer 2002). These and other studies, however, show little or no effect on mortality or even behavior at greater distances where the levels of sound were probably considerably lower (e.g., Feist and Anderson 1992; Bonar 1995; Shin 1995; Nedwell et al. 2003). However, these data are hard to extrapolate between pile driving experiments and often lack sufficient controls or observations.

For example, while a number of studies show that pile driving will cause fish death, they only account for fishes that come to the surface and were seen by observers (e.g., Caltrans 2001). They do not account for animals that may not have come to the surface, fishes without swim bladders that may be less affected by exposure to high sound pressure levels, and fishes that may have received some damage (e.g., to blood vessels) but which later healed, which died later, or which did not die but were in sufficiently bad shape to be more subject to predation than non-exposed fish.

As indicated by Trasky (1976), another area of uncertainty is the potential effect on the swim bladder of the large negative pressure (also see page 34). While Caltrans (2004) hypothesize this may have played a role in one group of surfperch that had 31% mortality, other important factors for mortality such as body mass and actual amount of received sound energy (not SEL) are unknown in their study. Because Bailey et al. (1996) found no difference between positive and negative peak overpressures in damage of lung tissue in mice submerged underwater and exposed to a controllable transient waveform, this issue needs to be examined to determine if it makes any difference in fish. The effects of exposure to pile driving sound that are primarily attributable to only the temporal characteristics of the waveform are unknown.

To use the existing scientific literature to address potential effects of sound caused by impact pile driving on Pacific Coast species, it is not sufficient to simply extrapolate information by comparing species that are taxonomically related. Ideally, fishes should be compared based on biomechanical properties of their swim bladder and any other internal gas-filled chambers, hearing capabilities (e.g., specialist vs. non-specialist), and then other aspects of their behavior. However, when such data are not available, it is probably more appropriate to extrapolate between species that have somewhat similar auditory structures or pressure detecting mechanisms (most notably the swim bladder) and species of similar size, mass, anatomical variation, and behavior relative to location of the fish in the water column. This would enable at least a first-order approximation of extrapolation to fishes such as Salmoniformes and other teleost fishes that, presumably, do not have hearing specialization (e.g., rockfish, bass). The results are less easily extrapolated to teleosts without a swim bladder (e.g., the flatfishes such as plaice, sole, and flounder, and gobies) and to fishes with very different ear structures than teleosts such as the sharks and rays, and the chondrosteans such as sturgeon. There are several hearing specialists found on the Pacific Coast, including sardines and cod, and it may be possible to get some indication on the effects of exposure to sound on these species from the few relevant studies on hearing specialists. But again, extrapolation must be done with considerable caution.

The body of scientific and commercial data available is inadequate for the purpose of developing final scientifically supportable guidance for exposure to pile driving sound that will protect fish. Most available data were obtained in experiments in which the sounds were not representative of those produced during pile driving. However, the information from explosive blast and pure tone studies is of some use to enable development of preliminary guidance addressing injury and mortality. At the same time, it is imperative to recognize the need for well-controlled studies to enable investigators to provide clear direction for development of final scientifically supported criteria. This conclusion is based on several factors.

(1) Most importantly, the signals used in all of the earlier potentially relevant studies are completely different from the signals emitted by pile driving (Table 3, page 26). As a consequence, the effects of such sounds, whether they be from air guns, blasts, or pure tones, are likely to be very different on both hearing and physiology compared to sounds produced by pile driving.

(2) There are insufficient data on the effects of any exposure to sound on fish. The data in the literature are incomplete, only relevant to specific species, and not easily extrapolated to other species. Moreover, each of the studies, including those of the authors of this report, was not focused on issues that relate to pile driving. As a consequence, the results

are not directly applicable to deriving final guidance for protecting fish during pile driving.

(3) None of the earlier studies used species that are necessarily similar to those found on the Pacific Coast. Because there is wide diversity in ear structure among fishes, and potentially in other aspects of their physiology, it is not reasonable to use the very small body of literature currently available to attempt to extrapolate to Pacific Coast fishes. In effect, the data in the literature pertain to the species studied, and none others. At the same time, results from earlier studies provide some guidance in developing hypotheses as to what might be expected for the specific species in question, and in design of experiments that could test these hypotheses.

(4) It is likely that thresholds for hearing effects will differ from effects on other aspects of fish physiology. Whereas there are significant differences in how fishes hear, the responsiveness of soft tissues (e.g., blood vessels, kidneys) are not likely to be very different between species (at least based upon current knowledge). However, the most severe damage in non-auditory tissues will occur at an interface with an internal gas-filled chamber because the interface will move when the gas responds to the force exerted by sound pressure. Therefore, fishes with different hearing thresholds and bandwidth may show very different auditory system damage attributable to the same pile-driving signal. Likewise, fishes with different swim bladder structural properties and shapes may show very different soft tissue damage (including swim bladder rupture) attributable to the same pile-driving signal. (At the same time, there is some question as to whether the organ system effects would differ between physostomus and physoclistus fishes, or occur at all in fishes that do not have a swim bladder. While data from Yelverton et al. (1995) suggest that fishes with both types of swim bladders are affected in the same way by explosive blasts, it is important to still question whether the same results would be found for both types of fishes for other types of sound, especially those with longer rise times and/or fall times that would allow time for a biomechanical response of the swim bladder. Similarly, work by several groups (Coker and Hollis 1952; Gaspin 1975; Baxter et al. 1982; Geortner et al. 1994) suggests that the effects of explosives on fishes without a swim bladder are different from that of fishes with a swim bladder. Thus, if internal damage is, even in part, an indirect result of swim bladder damage, fishes without this organ may show very different secondary effects after exposure to high sound pressure levels.)

(5) Analysis of effects may not only be species specific, but also mass specific, as demonstrated by the limited explosive blast data (Yelverton et al. 1995). Whether the same findings would hold up for exposure to pile driving sound is unknown, but the possibility that such an effect exists precludes defining final fish protective criteria for pile driving.

(6) None of the earlier studies have investigated effects of cumulative exposure to any type of sound. Moreover, no studies have done a careful examination of effects on fishes that are some distance from the source (where they may be exposed to lower levels of sound, but for longer periods of time) and whether there are subtle and long-term effects on behavior or physiology that could lead to an impact on survival of fish populations.

It is recognized that preliminary guidance is needed for protection of fish subjected to pile driving even as controlled experiments are conducted that will allow development of scientifically based criteria for exposure to pile driving sound. It should be noted, however, that it is likely that development of such criteria for pile driving will take several years of laboratory and field experiments with a number of different fish species.

Table 4 summarizes our recommendations for preliminary guidance. Preliminary guidance for immediate mortality and physical injury from a single sound exposure is based on the impulse data summarized in Yelverton et al. (1975). The basis for this is three-fold. First, the impact sound from pile driving has temporal and spectral characteristics similar to that of impulse sound generated from explosive blasts. Second, Yelverton et al. (1975) provided raw data in their report that could be analyzed to estimate SEL. Third, the recommendations in Table will therefore be conservative because explosive blast signals accumulate sound energy faster than impact signals from pile driving (see Appendix B).

The 50% mortality estimate was the primary basis for immediate mortalitybecause it correlated directly with their measured data as shown in Figure 7 (page 71). The 1% mortality and no injury lines in Figure 7 were not used because they are based on extrapolation of the Yelverton et al. (1975) data. The impulse, peak pressure, and cut-off time summarized in the data tables found in the Appendix of Yelverton et al. (1975) are needed to estimate the SEL as described in Appendix A of this report. Because the 1% mortality and no injury lines in Figure 7 are extrapolations, there were no peak pressure and cut-off time data associated with them to estimate SEL. Instead, the guidance for no physical injury in Table 4 is based only on data designated as "no injury" in the tables provided in the Appendix of the Yelverton et al. (1975) report.

Appendix B presents mortality and injury data for pile driving and blasts to show how they correlate with the preliminary guidance based on SEL estimated using data from Yelverton et al. (1975). Because the overpressure of an explosive blast has significantly faster rise and fall times and reaches higher levels than those typical of pile driving sounds, the injuries and mortalities reported by Yelverton et al. (1975) are probably more severe than what would be expected from exposure to a pile driving signal having the same SEL. In addition, it is important to note that SEL estimated from these data are also considered to be conservative because instrumentation used by Yelverton et al. (1975) was not capable of recording most of the peak pressures; consequently, their data were "clipped," meaning that they indicate a lower peak pressure and impulse than actually occurred (Hempen and Keevin 1995). Yelverton et al. (1975), however, did estimate the peak pressure from the slopes of the rising and falling portions of the pressure waveform, as is typically done when data is clipped.

Recommendations for preliminary guidance for auditory damage and hearing loss in Table 4 are based on pure tone studies because these signals have repeated pressure rise and fall times that are similar to those of multiple pile driving signals. In the studies used as a basis for these recommendations, fish were repeatedly exposed to positive and negative peak pressures at high levels for time periods of an hour or more. The levels recommended as interim guidance for hearing loss are ones that produced no damage to auditory hair cells, and in the case of the

goldfish, a fully recoverable TTS (Popper and Clarke 1976). Therefore these recommendations are conservative.

Table 4: Recommendations for Preliminary Guidance for Teleost Fishes

Issue	Hearing Generalists	Hearing Specialists
Immediate Mortality	Figure 8 (page 72) (upper line) shows preliminary guidance based on sound exposure level (SEL) estimated by approximating Yelverton et al. (1975) blast impulse data for 50% mortality with an idealized Friedlander wave as described in Appendix A (page 74).	See Figure 8. (upper line)
Delayed Mortality	No data available to provide guidance on whether there is damage that results in death minutes, hours, or days after exposure, or whether there are cumulative effects that could result in delayed death.	
Physical Injury	Figure 8 (page 72) (lower line) shows preliminary guidance based on sound exposure level (SEL) estimated by approximating Yelverton et al. (1975) blast impulse data designated as "no injury" with an idealized Friedlander wave as described in Appendix A.	See Figure 8. (lower line)
Auditory Tissue Damage	Exposure to a cumulative acoustic energy of 6000 J/m^2 at a frequency (or frequencies) in the most sensitive auditory bandwidth; primarily based on Hastings et al. (1996)	Equivalent to 1-hour continuous exposure to a pure tone, 120 dB above auditory threshold for sound pressure, in most sensitive bandwidth; primarily based on Hastings (1995).
Hearing Loss	Exposure to a cumulative energy of 1200 J/m^2 at a frequency (or frequencies) in the most sensitive auditory bandwidth; primarily based on Hastings et al. (1996).	Equivalent to 1-hour continuous exposure to a pure tone, 100 dB above auditory threshold for sound pressure, in most sensitive bandwidth; primarily based on Popper and Clarke (1976) and Hastings (1995).
Behavioral Effects	No data available with regard to behaviors such as swimming away from feeding or reproductive areas, changes in migration routes, etc. Data from use of seismic air guns (e.g., Skalski et al. 1992; Engås et al. 1996; Engås and Løkkeborg 2002) indicate that fish may move from fishing areas in response to those signals, but the relevance to pile driving is not clear; though one study on a coral reef showed little or no effect on overall behavior and movement patterns of fish and invertebrates (Wardle et al. 2001).	

It must be recognized that these recommendations: (a) are *only relevant to pile driving* and cannot be extrapolated to other sources of underwater sound such as air guns, ships, and sonars, because they are based on results of effects studies that used signals with temporal and spectral characteristics similar to those of pile driving signals; (b) may not be relevant to all pile driving activities; and (c) may not be relevant to all aquatic organisms.

B. Recommended Studies

To better understand the effects of pile driving on fishes there are three basic types of scientific study needed. First, a series of experiments should be conducted to characterize the sounds emitted by pile driving in different underwater environments. These data would be used to understand the signals that could affect fish and also to define a set of signal parameters that could be used to understand the acoustical properties specific to pile driving. Such an analysis would enable investigators to share a common set of signals that represent the received sound from the various types of piles, installation methods (including types of hammers), and sound mitigation techniques. Equally important, various agencies interested in the effects of pile driving on fishes would not have to develop their own set of signals characteristic of pile driving operations.

Second, a series of laboratory experiments needs to be conducted that uses the pile driving signals developed in the first series of experiments to evaluate the specific effects of pile driving on fishes. These studies would encompass behavioral to pathological effects. In all cases, the studies must be conducted under highly controlled conditions that provide data that is most useful to agencies and regulators.

Third, a series of field experiments needs to be carefully designed and conducted to verify results of the laboratory studies, especially those pertaining to behavioral effects. Most of the significant behavioral effects can be studied only in the field over long periods of pile driving activity. An ideal solution would be to set up a dedicated field test site with a single pile and hammer, or with a suitable underwater sound projector and instrumentation that could playback pile driving sounds for extended periods. If this is not possible then field experiments should be planned and conducted in close coordination with the construction activity to enable collection of critical data in a timely manner.

More specifically, the following guidelines should be followed in all experiments:

1. All studies should involve what are called “representative species.” Representative species are defined as those that serve as models for fishes in the region of question – in this case, the Pacific Coast. Species are selected to represent differences in: (a) habitat; (b) presumed hearing capabilities; (c) differences in ear structure; (d) differences in the connections between the ear and peripheral anatomical structures (e.g., swim bladder) that appear to enhance hearing capabilities; (e) bony fish and non-bony fish (including elasmobranchs); and (e) other comparable factors. A minimum set of fishes should be defined so as to have the fewest possible studies and yet represent as many of the parameters for fishes in the area of question as possible. At the same time, since these are going to be (logistically) difficult experiments to do, and take a good deal of time, additional priorities should be set up to select perhaps two species for initial study. Results from such studies would enable investigators to (a) develop detailed methods, (b) get data that would guide future experiments as to signal types, etc., and (c) provide data that might be applicable to a broad range of other related species.

2. All studies must be done in a way to provide maximum observer reliability. While the ideal experiments would use “double-blind” methods to prevent observer bias, recent field studies

on the effects of seismic air guns (Popper et al. in prep. b) and SURTASS LFA sonar (Popper et al. in prep. a) have shown that double-blind studies do not allow rapid response to changing environmental and experimental conditions in field studies. At the same time, developing methods for laboratory studies would allow for double-blind studies and these should be used wherever possible.

3. Experimental studies must be conducted using an appropriate statistical design (perhaps with involvement of a statistician familiar with design of these kinds of experiments) so that the results are sufficient for statistical analysis and have a sufficiently high statistical confidence.

4. Results of experimental studies should be published in peer-reviewed scientific journals.

5. Suitable controls must be provided, subjecting animals to precisely the same experimental conditions other than exposure to the sound treatment (e.g., Abbott 2004). In addition, a second set of baseline controls is generally made up of animals that have not been subject to any manipulation whatsoever (see Abbott 2004; Caltrans 2004; Popper et al. in prep. a, b).

6. Individuals who are expert in the appropriate techniques must do all work. In particular, individuals who do pathological studies must follow accepted practice for doing necropsy and be expert in histologic pathology (e.g., Kane 1996; Kane et al 2000; Govoni et al. 2003; Marty 2004).

7. Studies that determine hearing sensitivity and hearing bandwidth of representative species must be done in a way that allows for presentation of both pressure and particle motion signals, and with full calibration of the sound field, including pressure and particle motion. Similarly, the acoustic field must be known and calibrated for all other studies of hearing.

8. All exposure experiments must be done in a laboratory chamber or facility with a defined acoustic field that has a known relationship between sound pressure and acoustic particle velocity. In a laboratory, special waveguides or larger facilities are required to achieve this underwater (see for example, Finneran and Hastings 1999; Wang et al. 1998). Such laboratory studies will enable investigators to define the components of the sound field that have the greatest impact on fishes. Moreover, properly designed, these studies should enable a clear definition of the signal parameters that should be used in defining criteria (e.g., peak pressure, total energy flux, rise time, etc.)

9. Finally, and in order to develop guidelines and subsequent criteria, there need to be controlled field experiments to validate the findings from the laboratory. The controlled field studies should include comprehensive visual monitoring of fish behavior in direct response to pile driving sounds. If a dedicated field test site is not feasible, then these studies should be devised to optimize the experiment with the pile driving schedule for an extended period of time to allow for the appropriate types of studies, the appropriate number of replicates, and appropriate controls.

The most important data that must be acquired to evaluate effects of exposure to pile driving sound on fishes are presented in Table 5 (pages 49 - 52).

Table 5: Research Questions on the Impact of Pile Driving on Fishes

Project title	Project Objectives	Significance	Relationship to other studies	Relationship to pile driving needs
Characterize Pile Driving Sounds				
Define acoustic dose for exposure to pile driving sound	Develop ways to express exposure to pile driving sounds in terms of total energy received and the degree of temporal variation in the waveform, and to define the acoustic particle velocity within the sound field	This will provide a series of "standard" pile driving sounds in water and substrate for use as the stimuli with which to do studies on representative species	This study is fundamental to investigations of effects on fishes because it provides laboratory signals that would be representative of the range of pile driving stimuli in different locations	Without this standardization it will be impossible to generalize between studies done in different locales and with different piles
Structural acoustic analysis of piles	Develop structural acoustics models of piles to investigate how modifications to piles and hammering could alter the sounds and potentially incur less damage to animals	This could result in potential modifications to the structure, hammer, and/or process that could reshape the temporal characteristics of the pile driving stimulus without changing structural integrity	Would need to test modified sounds on animal models	This analysis will help provide ways to mitigate some effects of pile driving on aquatic organisms
Define characteristics of the underwater sound field	Develop underwater sound propagation model and integrate with pile structural acoustics models to estimate received levels of sound pressure and particle velocity in the vicinity of pile driving operations and verify with field measurements of underwater sound pressure measurements	This is the only way to define zones of impact on fishes because the sound energy received by a fish depends on not only the pile-driving source, but also the size, shape, and properties of the underwater environment.	Would be able to map the impact of pile driving sounds on the underwater environment based on results of tests of pile driving sounds on animal models	Received levels of sound pressure and acoustic particle velocity must be known underwater in the region surrounding the pile to calculate appropriate metrics related to observed effects and define the zone of impact

Continued next page

Project title	Project Objectives	Significance	Relationship to other studies	Relationship to pile driving needs
Characterize injury of fish exposed to pile driving sounds **(see Figure 9, page 73)**				
Hearing capabilities of Pacific Coast fishes	Determine hearing capabilities (using Auditory Brainstem Response [ABR]) of representative species. Determine in terms of both pressure and particle motion.	Useful for prediction of detection range of pile driving sounds and potential effects on hearing capabilities	Previous behavioral studies did not use any Pacific Coast fishes or elasmobranchs	Studies would be on species that are particularly germane to those affected by pile driving
Mortality of fishes exposed to pile driving	Determination of short and long term effects on mortality of representative species as a result of pile driving. Measure pathology (using necropsy studies) of the effects on fishes of received sounds representative of different distances from the source	Provide baseline data on effects of pile driving and the effects of such signals of different levels and spectral components	Studies of this type have, heretofore, not be done under controlled situations	Provide mortality data as well as pathology as to the effects of pile driving and determination of the cause of immediate and long-term mortality
Effects of pile driving on non-auditory tissues	Using the precise same paradigm as for effects on the ear, examine other tissues using standard fish necropsy techniques to asses gross, cellular, and molecular damage to fish. Furthermore, determine stress effects on fish using appropriate stress measures (e.g., hormone levels). Do for representative species.	Provide insight into how the sounds affect fish, even when there is no immediate mortality	The only comparable data are from blasts, which suggests significantly different effects depending on fish size and species.	Direct measure of potential long-term damage to fishes.
Effects of pile driving on hearing capabilities	Determine TTS and PTS on representative species.	Provide insight into hearing loss and possible recovery as a result of different sound levels and sound types	No studies of this type have been done using pile-driving sounds	Data that will help understand the sound levels and other parameters that could result in the loss of the ability of different species types to detect sounds, and thus detect biologically critical signals
Effects of pile driving on fish eggs and larvae	Determine mortality, growth rates, and pathological changes in developing fishes of representative species with exposure at different times during the development cycle	Since eggs and larvae do not move from the sites of spawning, determine if long-term pile driving could affect fish populations	No studies done on any fish system are relevant to this investigation	If fish spawn in the vicinity of pile driving sites, or cannot be kept from spawning during pile driving operations, effects on eggs and larvae could be considerable Continued next page

Project title	Project Objectives	Significance	Relationship to other studies	Relationship to pile driving needs
Behavioral responses of fish to pile driving	Observe, in large-scale cages, the short-term behavioral responses of representative species to pile driving sounds. Do fish attempt to swim from the source? Do they react to the sounds? Do they "freeze" in place?	In knowing behavioral responses, it may be possible to predict which species would remain in an area of pile driving vs. species that could be expected to leave the area after the initial pile driving activity.	None have been done to date.	This may help limit the number of species that would need to be "protected."
Long-term behavioral effects of pile driving on fish	Attempt to do field studies that would provide insight into movement patterns of fishes and normal behaviors and how these might be affected, in the long-term, by the presence of continuous pile driving.	While there may be few or no apparent effects on immediate behavior (e.g., rapid swimming), physiology (e.g., hearing, effects on other organs), or mortality, there may be longer-term behavioral effects such as those from continual sounds from pile driving preventing fish from reaching breeding sites, finding food, hearing and finding mates, etc. This could result in long-term effects on reproduction and population survival.	None have been done to date.	Pile driving may not have an immediate impact on fishes, but continual pile driving may have longer-term effects that could significantly alter fish populations in the areas in which pile driving takes place.

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Project title	Project Objectives	Significance	Relationship to other studies	Relationship to pile driving needs
Effects of pile driving on the ear and lateral line	Determine morphological changes over time for representative species on sensory cells of the ear and lateral line, and whether such changes are reversible	If there is loss of sensory cells there is a loss in hearing ability or the ability of the lateral line to be used in hydrodynamic reception. If there is recovery of these cells, fishes may be able to survive (assuming they did not die prior to recovery).	A few studies suggest that exposure to high sound pressure levels will affect the sensory cells of the ear, but almost nothing is known about the lateral line. However, no studies were done with sounds comparable to those from pile driving	Loss of hearing capabilities, even for a short period of time, could dramatically affect survival of fishes.
Effects of multiple pile driving exposures on fish	For the appropriate experiments cited above, determine effects of multiple exposures, over time, of pile driving	Some fishes may stay in the pile driving area, or go between areas that have different time tables for pile driving. Thus, there may be multiple exposures over time	No data in the literature.	If fish remain in an area over time, there may be cumulative effects that need to be understood

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Glossary

Acoustic energy flux – The work done per unit area and per unit time by a sound wave on the medium as it propagates. The units of acoustic energy flux are Joules per square meter per second (J/m^2-s) or watts per square meter (W/m^2). The acoustic energy flux is also called acoustic intensity.

Acoustic particle velocity – The time rate of change of the displacement of fluid particles created by the forces exerted on the fluid by acoustic pressure in the presence of a sound wave. The units of velocity are meters per second (m/s).

Acoustic Pressure – The force per unit area exerted by a sound wave above and below the ambient or static equilibrium pressure is called the acoustic pressure or sound pressure. The units of pressure are pounds per square inch (psi) or, in the SI system of units, Pascals (Pa). In underwater acoustics the standard reference is one-millionth of a Pascal, called a micro-Pascal (1 μPa).

Acoustic threshold – See "Threshold."

Ambient sound – Normal background noise in the environment, which has no distinguishable sources.

Amplitude – The maximum deviation between the sound pressure and the ambient pressure.

Arterial air embolism – Blockage of an artery created by the entrance of air into the circulation as a result of trauma. Death can occur if an embolus of air obstructs the brain or heart circulation.

Auditory Brainstem Response (ABR) – A physiological method to determine hearing bandwidth and sensitivity of animals without training (e.g., Casper et al. 2003; Smith et al. 2004a, b). Electrodes (wires) are placed on the head of the animal just outside of the base of the brain (brainstem) to record electrical signals (emitted by the brain) in response to sounds that are detected by the ear. These signals are averaged and used to determine if the animal has detected the sound. It is possible to determine auditory thresholds for fishes using this method. The same method is used for numerous other species, including measurement of hearing capabilities of newborn human babies.

Bandwidth – The range of frequencies over which a sound is produced or received.

Continuous wave exposure – Insonification by a sound wave that is continuous in time.

Cumulative pressure squared – The time-integrated value of the square of the sound pressure over a certain time period.

Decibel (dB) – A customary scale most commonly used (in various ways) for reporting levels of sound. A difference of 10 dB corresponds to a factor of 10 in sound power. The actual sound measurement is compared to a fixed reference level and the "decibel" value is

defined to be 10 $\log_{10,}$(actual/reference), where (actual/reference) is a power ratio. Because sound power is usually proportional to sound pressure squared, the decibel value for sound pressure is $20\log_{10}$ (actual pressure/reference pressure). As noted above, the standard reference for underwater sound pressure is 1 micro-Pascal (µPa). The dB symbol is followed by a second symbol identifying the specific reference value (i.e., re 1 µPa).

Ensonification - The words, "insonify" and "ensonify," are often used as synonyms but, in fact, they have subtle but different meanings. "Sonify" is a verb that simply means, "to add sound." It's traditionally used when sound is added for an effect, either to interpret scientific data (e.g., a Geiger Counter) or to enhance an experience (such as to sonify a video game). When "en" is used as a prefix to a verb to form another verb, then it means "so as to cover thoroughly" as in "enwrap." In contrast, the prefix, "in," means "within" or "into." Examples of "in" added to a verb to form another verb are "inlay" and "input." Likewise "insonify" means "to add sound into."

With regards to exposure to sound, "emission" refers to sound from the source and "immission" refers to sound received by a person or animal. If we are intentionally putting sound into an animal (or other target) to determine its effects on behavior, annoyance, hearing, etc., then we are "insonifying" that animal or target. But if sound is being emitted into a region, for example from a fog horn, then it is "ensonifying" as far its "emission" will travel and it may not "insonify" anything.

Fall time – The amount of time it takes to go from the peak pressure to either zero pressure or the minimum pressure in an impulsive sound wave.

Far field – A region far enough away from a source that the sound pressure behaves in a predictable way, and the particle velocity is related to only the fluid properties and exists only because of the propagation sound wave (see Near field).

Frequency spectrum – See Spectrum.

Gas bladder – See Swim bladder.

Hertz – The units of frequency where 1 hertz = 1 cycle per second. The abbreviation for hertz is "Hz."

Impulse – See Impulse sound.

Impact sound – Transient sound produced when two objects strike each other and release a large amount of mechanical energy. Impact sound has very short duration but relatively high peak sound pressure.

Impulse sound – Transient sound produced by a rapid release of energy, usually electrical or chemical such as circuit breakers or explosives. Impulse sound has extremely short duration and extremely high peak sound pressure.

Impulse length –The total amount of time it takes for the impulse to occur.

Impulse width – The time required to go from a minimum or zero pressure to the peak pressure and then back to the minimum or zero again.

Infrasound – Sound at frequencies below the hearing range of humans. These sounds have frequencies below about 20 Hz.

Insonification – Irradiation with sound energy. See “ensonification” for complete differentiation between insonification and ensonification.

Lagena – One of the three otolithic end organ of the inner ear of fishes. The precise role of the lagena is not defined, but it is likely that it is involved in sound detection in many species. The lagena is also found in all terrestrial vertebrates other than mammals, where it may have evolved into the mammalian cochlea.

Lateral line – A series of sensors along the body and head of fishes that detects water motion. The lateral line uses sensory hair cells (identical to those in the ear) for detection. The cells are located in neuromasts that lie either in canals (e.g., along the side and head of the fish) or freely on the surface in a widely distributed pattern.

Near field – A region close to a sound source that, depending on the size of the source relative to the wavelength of the sound, has either irregular sound pressure or exponentially increasing sound pressure towards the source, and a high level of acoustic particle velocity because of kinetic energy added directly to the fluid by motion of the source. This additional kinetic energy does not propagate with the sound wave. The extent of the near field depends on the wavelength of the sound and/or the size of the source.

Otolith – Dense calcareous structures found in the otolithic end organs (saccule, lagena, utricle) of the ears of fishes. They are located next to sensory hair cells of the ear and are involved in stimulation of the ear for detection of sound or head motion.

Peak pressure – The highest pressure above or below ambient that is associated with a sound wave.

Peak overpressures – Overpressure is the pressure above the ambient level that occurs in an impulse sound such as an explosion. The peak overpressure is the highest pressure above ambient.

Permanent threshold shift (PTS) – A permanent loss of hearing caused by some kind of acoustic or drug trauma. PTS results in irreversible damage to the sensory hair cells of the ear, and thus a permanent loss of hearing.

Plane-traveling wave – A plane wave is an idealized sound wave that propagates in a single direction along its longitudinal axis. Theoretically the sound pressure is the same over an infinite plane that is perpendicular to the direction of propagation.

Physoclists – See Physostomes.

Physostomes- Fish species in which the swim bladder is connected to the esophagus by a thin tube. Air to fill the swim bladder is swallowed by the fish and is directed to the swim bladder. Air removal from the swim bladder is by expulsion through this tube to the esophagus. Physoclistus fishes have no such connection. Instead, they add gas to the swim bladder using a highly specialized gas secreting system called the rete mirabile which lies in the wall of the swim bladder and extracts gas from the blood using a counter-current system, much like that found in the kidney to remove wastes from the blood. Removal of gas from the swim bladder occurs by reabsorption into the blood.

Pulse – A transient sound wave having finite time duration. A pulse may consist of one to many sinusoidal cycles at a single frequency, or it may contain many frequencies and have an irregular waveform.

Rectified diffusion – Bubble growth by rectified diffusion occurs when more gas diffuses into a bubble while it is expanded (and at lower internal pressure) than the amount of gas that diffuses out when it is compressed (and at higher internal pressure). The amount of gas inside the bubble gradually increases and the bubble grows over time as it oscillates.

Resonance frequency – The frequency at which a system or structure will have maximum motion when excited by sound or an oscillatory force.

Rise time – The interval of time required for a signal to go from zero, or its lowest value, to its maximum value.

Saccule – One of the three otolithic end organs of the inner ear. It is generally thought that the saccule is involved in sound detection in fishes, although it also has roles in determining body position relative to gravity, its primary role in terrestrial vertebrates.

Shock wave – A propagating sound wave that contains a discontinuity in pressure, density, or particle velocity.

Sound attenuation – Reduction of the level of sound pressure. Sound attenuation occurs naturally as a wave travels in a fluid or solid through dissipative processes (e.g., friction) that convert mechanical energy into thermal energy and chemical energy.

Sound energy metric – A value that characterizes a sound by some measure of its energy content.

Sound exposure – The integral over all time of the square of the sound pressure of a transient waveform.

Sound exposure level (SEL) – The constant sound level acting for one second, which has the same amount of acoustic energy, as indicated by the square of the sound pressure, as the original sound. It is the time-integrated, sound-pressure-squared level. SEL is typically used to compare transient sound events having different time durations, pressure levels, and temporal characteristics.

Sound exposure spectral density – The relative energy in each narrow band of frequency that results from the Fast Fourier Transform (FFT - a mathematical operation that is used to express data recorded in the time domain as a function of frequency) of a transient waveform. It is a measure of the frequency distribution of a transient signal.

Sound pressure level (SPL) – The sound pressure level or SPL is an expression of the sound pressure using the decibel (dB) scale and the standard reference pressures of 1 µPa for water and biological tissues, and 20 µPa for air and other gases.

Spectrum – A graphical display of the contribution of each frequency component contained in a sound.

Swim bladder – A gas (generally air) filled chamber found in the abdominal cavity of many species of bony fish, but not in cartilaginous fishes. The swim bladder serves in buoyancy control. In many species the swim bladder may also serve as a radiating device for sound production and/or as a pressure receiving structure that enhances hearing bandwidth and sensitivity.

Temporary threshold shift (TTS) – Temporary loss of hearing as a result of exposure to sound over time. Exposure to high levels of sound over relatively short time periods will cause the same amount of TTS as exposure to lower levels of sound over longer time periods. The mechanisms underlying TTS are not well understood, but there may be some temporary damage to the sensory hair cells. The duration of TTS varies depending on the nature of the stimulus, but there is generally recovery of full hearing over time.

Threshold - The threshold generally represents the lowest signal level an animal will detect in some statistically predetermined percent of presentations of a signal. Most often, the threshold is the level at which an animal will indicate detection 50% of the time. Auditory thresholds are the lowest sound levels detected by an animal at the 50% level.

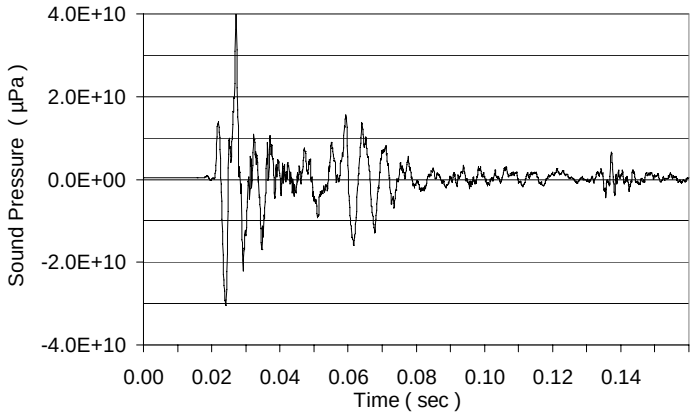
Total energy dose – The total cumulative energy received by an organism or object over time in a sound field.

Utricle – One of the three otolithic end organs of the inner ear of fish (the others are the saccule and lagena). The utricle is probably involved in determining head position relative to gravity as well as in sound detection. It is the primary sound detection region in the Clupeiform fishes (herrings, shads, sardines, anchovies, and relatives). A utricle is found in all vertebrates, including humans.

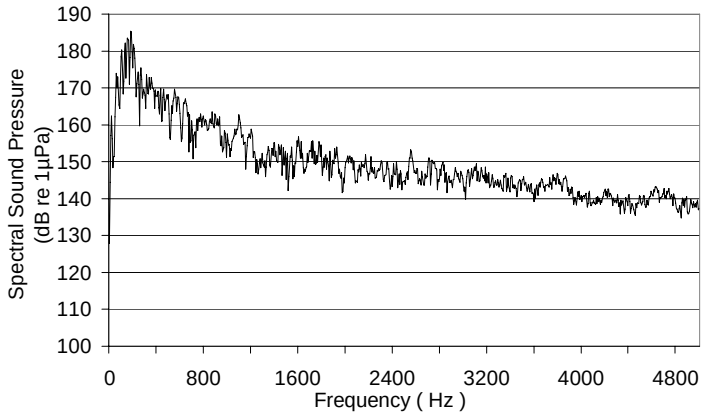
Waveguide – A device for guiding the propagation of waves, such as an air duct.

Weberian ossicles – A series of bones found in the otophysan fishes (goldfish, catfish, and relatives) that connect the swim bladder to the inner ear. It is generally thought that the Weberian ossicles act to couple the motions of the swim bladder walls in response to pressure signals to the inner ear. Thus, the ossicles are functionally analogous to the mammalian middle ear bones as acoustic coupling devices.

Figures



(a)



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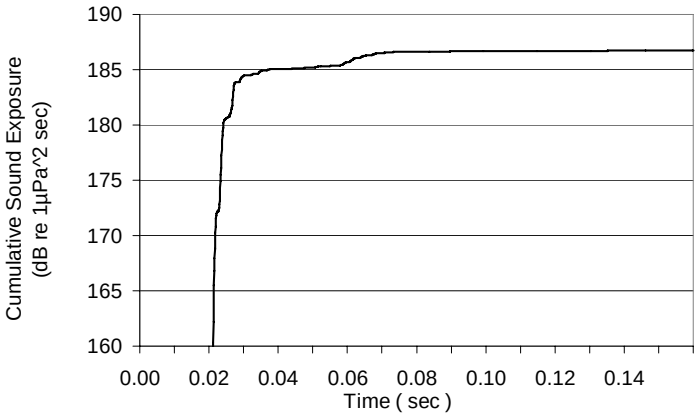
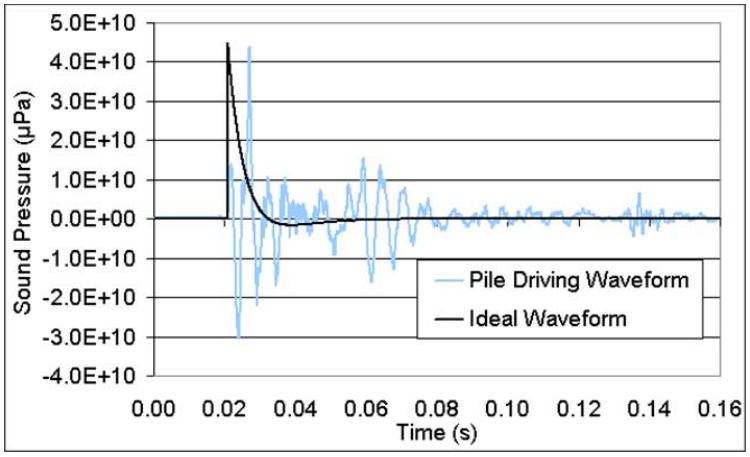
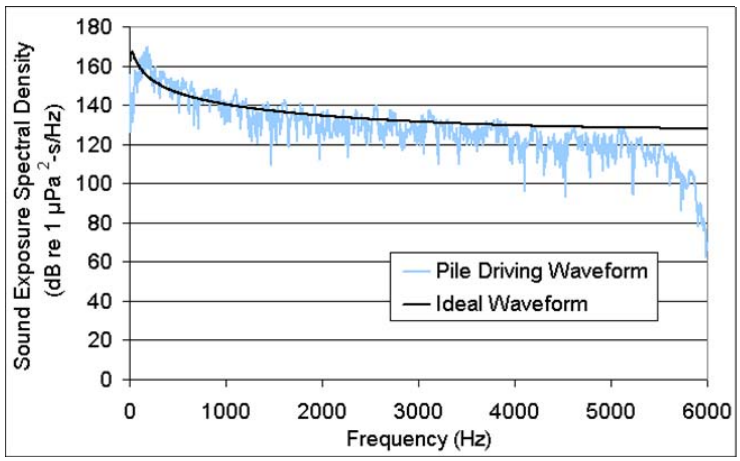


(c)

Figure 1: Measures of unattenuated pile driving sound at the San Francisco-Oakland Bay Bridge East Span Replacement project (SFOBB), Pier 3E at 50 m in relatively deep water. (a) Measured sound pressure waveform; (b) narrow-band frequency content of the waveform; (c) cumulative sound exposure (or sound pressure squared) over time. The sound exposure level (SEL) for this single hammer strike is 187 dB re 1 μPa^2-s and RMS (impulse) is 200 dB re 1 µPa (based on 0.048 s pulse width). Data provided by J. Reyff, Illingworth & Rodkin, Inc.



(a)



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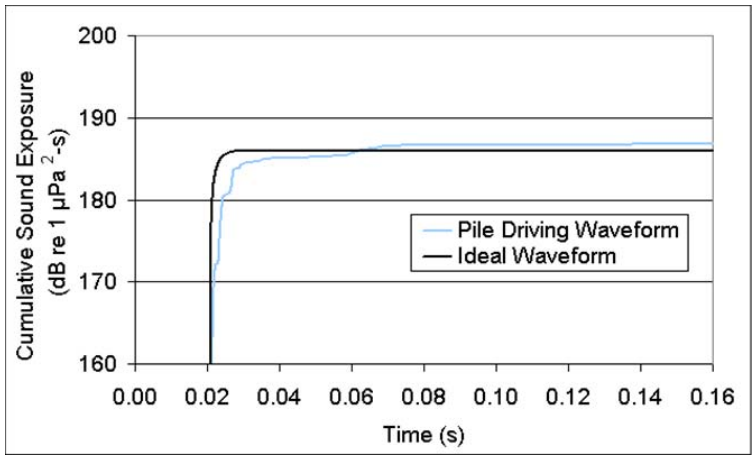

(c)

Figure 2: An ideal impulse wave, based on the Friedlander model, captures the major (a) temporal, (b) spectral, and (c) cumulative sound exposure (or sound pressure squared) characteristics of a real pile driving impulse. These types of analyses could be used to relate existing blast and sonic boom animal effects data to assess the impact of pile driving sounds on fishes, and to investigate the effects of shaping the pile driving sound pulse.

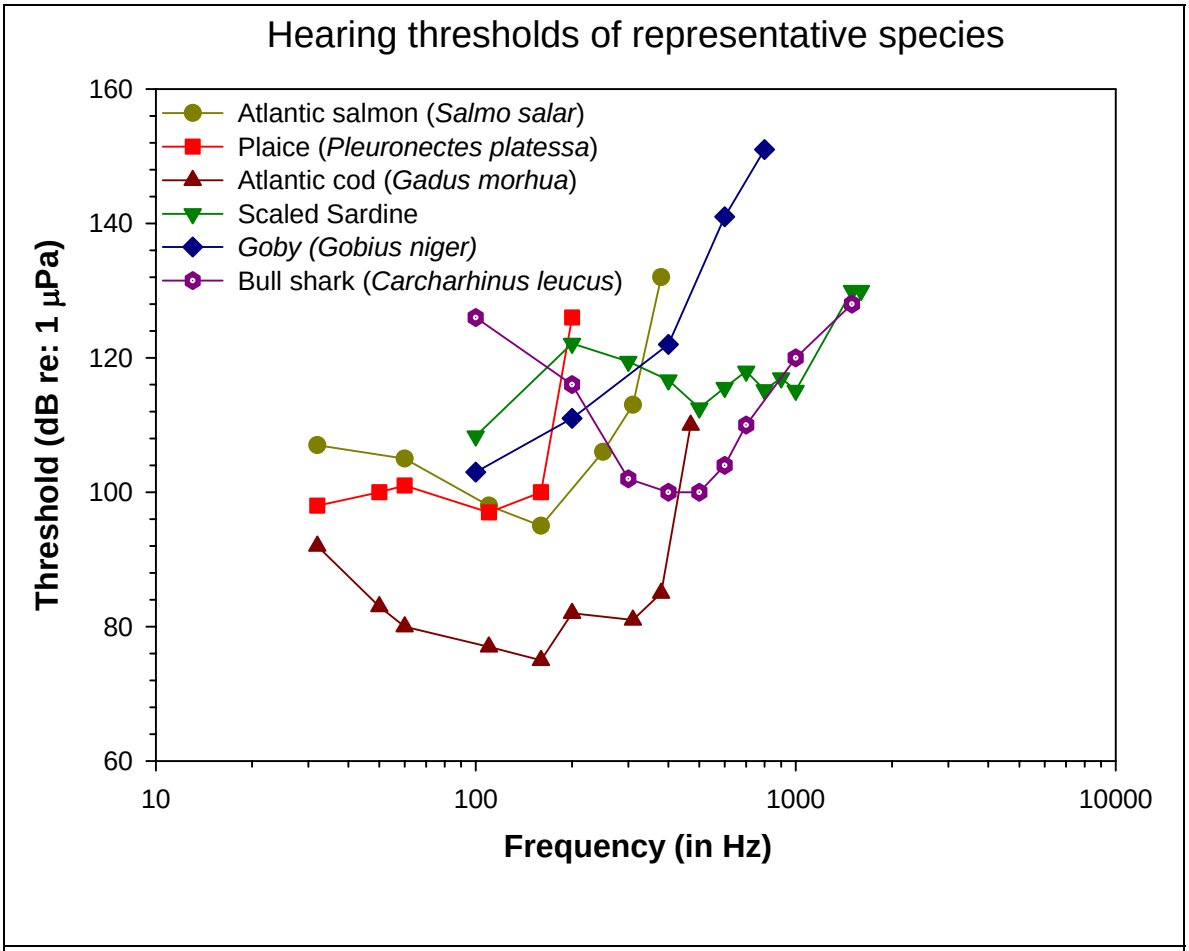

Figure 3: Hearing thresholds for species of fish that are similar to those found on the Pacific Coast. While data are not available for any of the species found in the Bay, these data suggest that none of the species, with the exception of the sardine (and related species) detects sounds much above 1000 Hz. It is important to note, however, that not all of the thresholds for hearing generalists plotted here or in other sources may be quantitatively valid because a number of these species probably do not respond to sound pressure (except, possibly the scaled sardine and Atlantic cod). It is likely, however, that the frequency range of best sensitivity of the generalists is reasonably accurate. Furthermore, the relatively poor sensitivity in a number of these species is probably qualitatively correct. To do more accurate measures, one would need to determine not only sound pressure, as done in the studies reported here, but also particle motion because that is what these fishes most likely are detecting. It should also be noted that the data for the bull shark are highly "suspect" and only represents determination with a few specimens. There are also recent data suggesting that salmonids (Atlantic salmon and related species) and flatfish (plaice and relatives) are able to detect infrasonic frequencies – sounds below about 35 Hz (e.g., Knudsen et al. 1992, 1994). Data in the figure were compiled from Fay 1988.

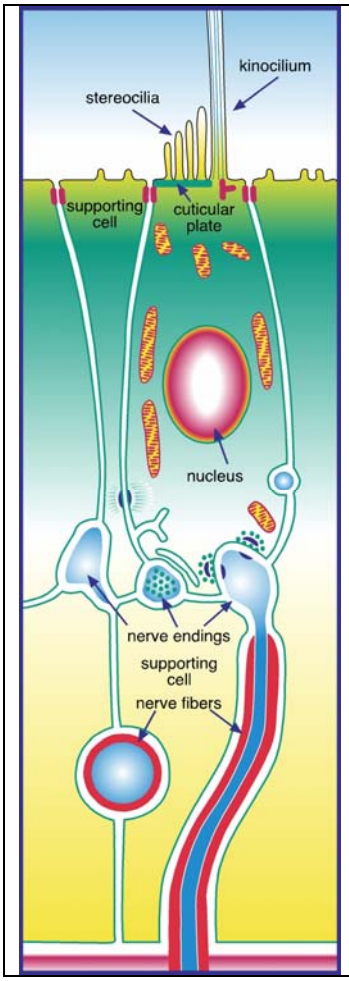

Figure 4. Schematic drawing of a sensory hair cell from a fish. The transducing element is the ciliary bundle, made up of the kinocilium and stereocilia, at the apical (top) end of the cell. This bundle is in contact with the otolith that lies in the chambers of the otolithic end organs (saccule, lagena, utricle). Relative motion between the sensory cell body sitting in the sensory epithelium and the overlying otolith results in a shearing or bending of the ciliary bundle. This causes channels (sub-microscopic holes) to open in the cilia and allowing the entry of calcium ions into the cell. This results in a cascade of events that leads to the release of chemical neurotransmitters from the base of the cell. The neurotransmitter crosses a small gap between cells and excites the endings of the nerve that innervates the cell. This, in turn, results in an electrical potential (the action potential) in the nerve that is carried to the brain. (From Popper and Coombs 1980)

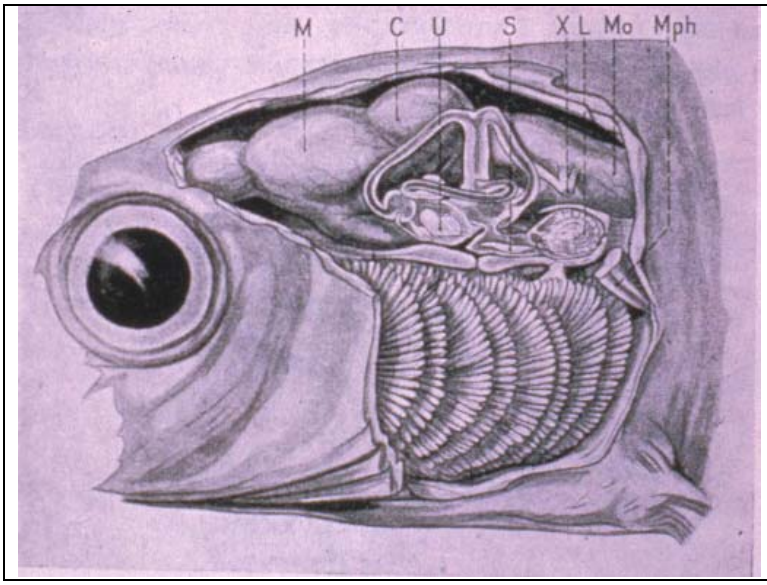

Figure 5. Lateral view of the head of a minnow *Phoxinus laevis* (from von Frisch and Stetter 1932). This picture shows the location of the ear in the brain cavity. It is located towards the rear of the brain and above the gills. This fish is a hearing specialist and so the ear is a bit different than that of a non-specialist as shown in Figure 5. M – medulla of brain; C – Cerebellum of brain; U – utricular otolithic end organ; S – saccule; L – Lagena; X – 10th cranial nerve (not associated with hearing)

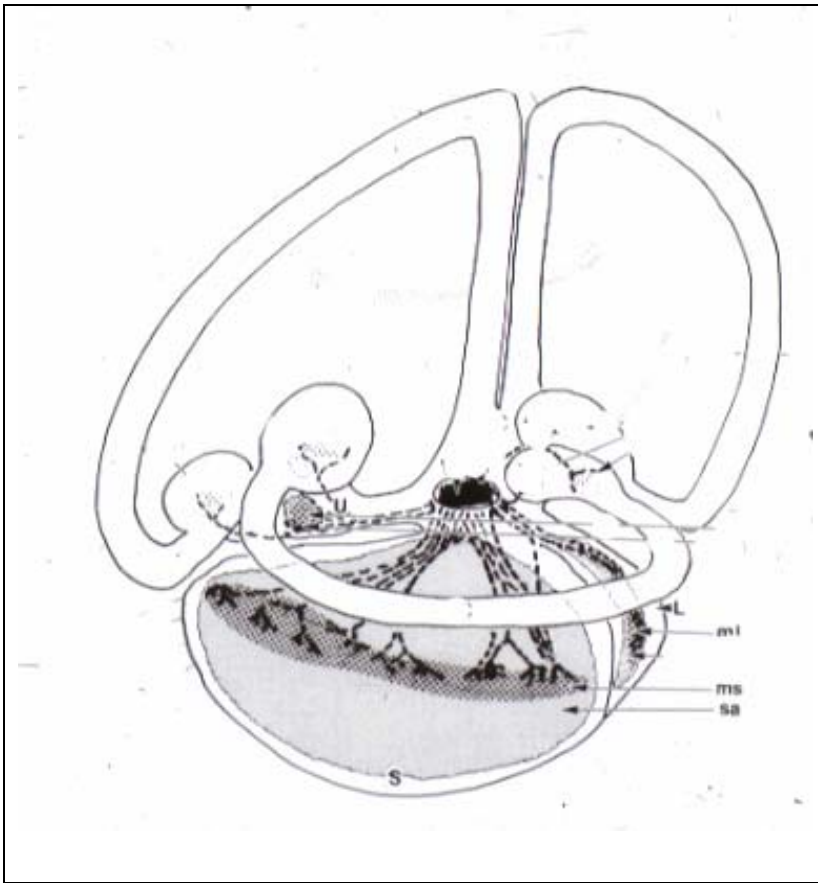

Figure 6. Drawing of the right ear of a salmon (*Salmo salar*). Anterior to the left and dorsal to the top. The drawing shows the three semicircular canals and the three otolithic end organs, the utricle (u), saccule (s), and lagena (L). The sensory epithelia of the saccule (ms) and lagena (ml) are shown, along with the saccular otolith (so). The utricle also has an epithelium and all three end organs have otoliths of different sizes. The ear is innervated by the eighth cranial nerve (the same one that innervates the mammalian ear). Drawing by Dr. Jiakun Song.

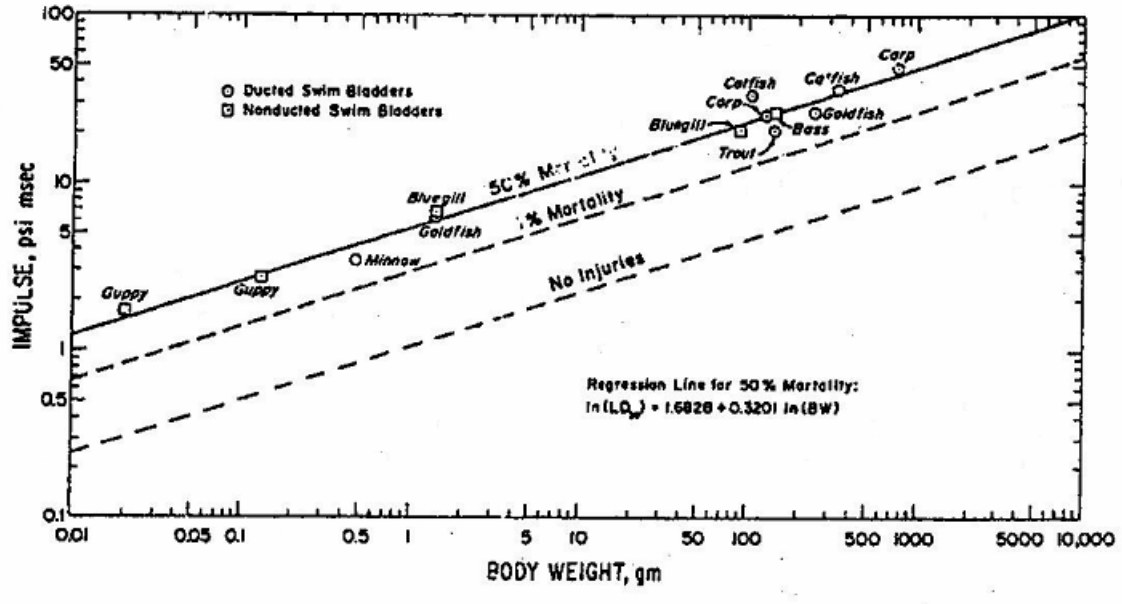

Figure 7: The results of study by Yelverton et al. (1975) to determine the effects of underwater blasts on fishes. A direct correlation was found between body mass and the received sound impulse, characterized by psi-msec, which caused 50% mortality. The correlation was independent of peak overpressure, thus indicating that sound energy may be more indicative than peak pressure in determining damage thresholds. Fish with ducted swim bladders were found to be just as vulnerable to blast injury and death as those without ducts. (Note: Yelverton et al. reported no control test specimens in this study.)

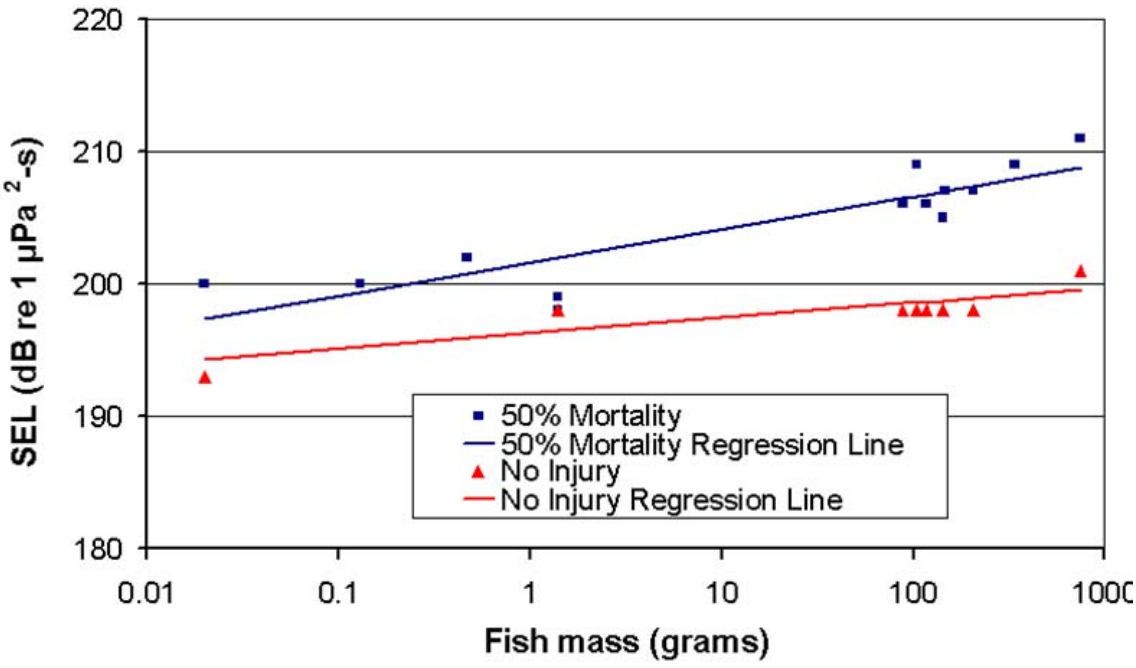

Figure 8: Estimated sound exposure level (SEL) that results in no mortality and 50% mortality based on data for exposures to a single explosive sound as reported by Yelverton et al. (1975) and modeled as an ideal impulse wave as described in Appendix A (page 74). (Friedlander waveform as described by Hamernik and Hsueh 1991).

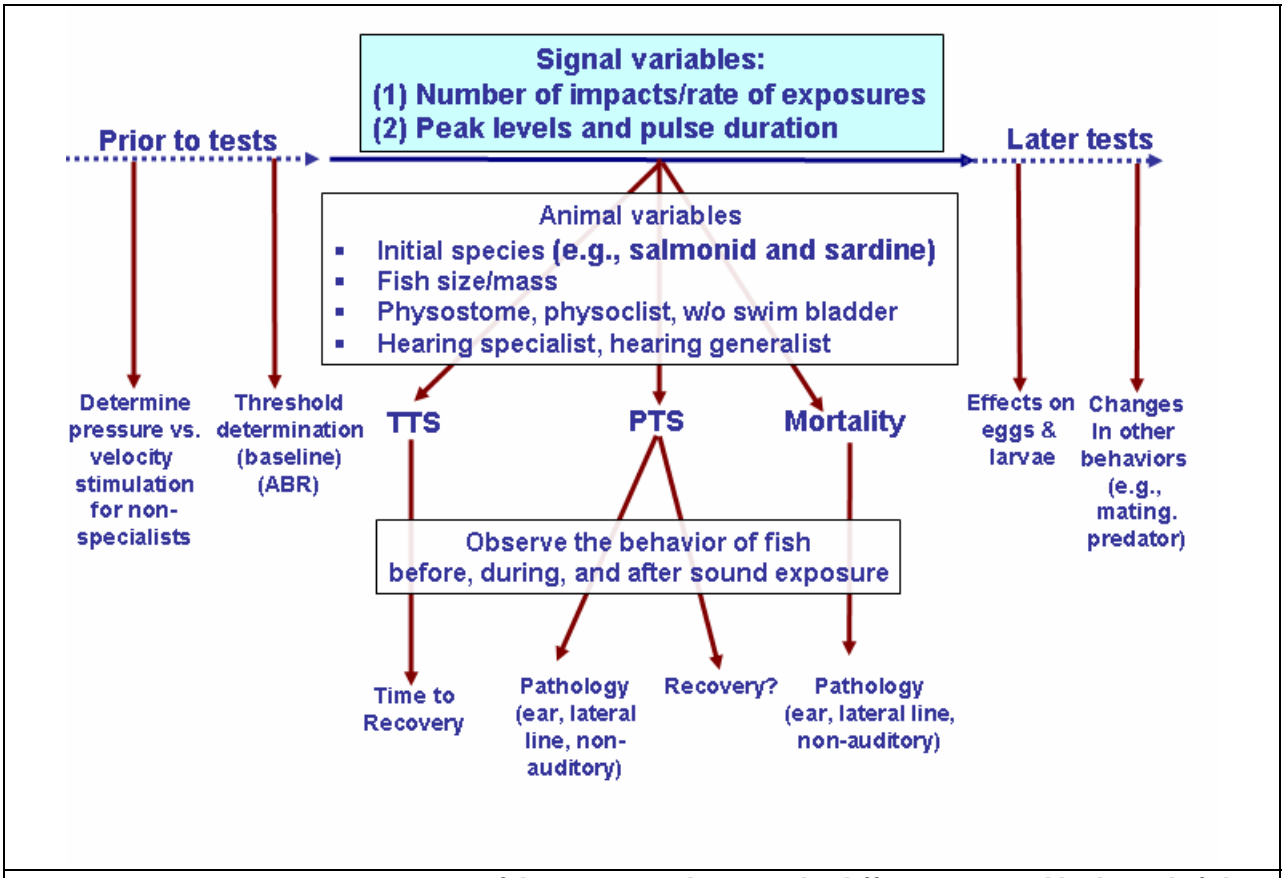

Figure 9: Diagrammatic representation of the interaction between the different proposed biological (fish) experiments. While eggs/larvae are considered for later study, they could potentially be included in some of the studies proposed. Behavioral studies listed for later include areas that range from changes in response to predators to reproductive behavior and general survival.

Appendix A

Comparing Pile Driving Waveforms with Ideal Blast Waveforms

A. Modeling a Pile-Driving Waveform with a Friedlander Waveform

The Friedlander wave provides a mathematical model for blast waveforms and other impulse signals (Hamernik and Hsueh 1991). If transient sounds, such as those produced by pile driving, could be characterized using a waveform similar to this type, then effects of pile driving on aquatic animals could potentially be extrapolated from data based on effects observed from exposure to impulsive signals (e.g., explosives, air guns, sonic booms) or other transient waveforms that could be described by the Friedlander wave model. These estimates could provide a basis for developing interim guidance for exposure to sound from pile driving until more research is completed.

The classic Friedlander wave is a shock wave with zero rise time to the initial positive pressure peak. However, a Friedlander wave with rise time can also be modeled mathematically as shown by Hamernik and Hsueh (1991). Using the symbol 'b' for rise time in seconds, and the symbol 'c' for the time it takes for the pressure to return to zero, this pressure waveform, P(t), as a function of time, t, can be expressed as:

$$P(t) = P_{pk}(1-(t-b)/c)e^{-(t-b)/c},$$

where P_{pk} is the peak pressure.

To approximate a pile-driving waveform using this model as illustrated in Figure 2(a) (page 67), 'b' was chosen to be the rise time of the first pressure peak and 'c' was chosen so that the pressure returned to zero at a time that approximately coincided with the knee of the accumulated energy curve. P_{pk} was chosen to be the peak pressure in the pile-driving waveform. In this example, both the initial change in pressure and the peak pressure in the pile driving waveform were positive. If either or both of these is negative, however, then 'b' and 'c' would be chosen with respect to the negative pressure values. So if the initial change in pressure were negative, then the initial fall time of the pile-driving waveform would be used as the rise time for the Friedlander wave. Likewise, if the peak pressure were negative, then its magnitude would be used to for the positive peak pressure, P_{pk}, of the Friedlander wave.

To determine if this Friedlander waveform is a good approximation of the pile-driving waveform based on equivalent acoustic energy (as determined by the pressure squared), its SEL was determined by calculating P(t) at the same time intervals used to record the pile driving waveform data and then summing the cumulative pressure squared values. This comparison was plotted in Figure 2(c). For this example the SEL of the original pile-driving signal was 186 dB (re 1 μPa^2-s) and the SEL of its Friedlander model was 187 dB (re 1 μPa^2-s). Figure 2(c) also indicates that the time rate of energy accumulation is approximately the same for both the original and modeled waveforms.

B. Using a Friedlander Waveform Model to Estimate SEL from Yelverton et al. (1975) Data

Because a Friedlander wave can provide an estimate of the SEL of a single pile-driving signal, then it would be reasonable to assume that the two could be compared if we estimate the SEL in the waveforms used by Yelverton et al. (1975) by also modeling them with a Friedlander model. Since Yelverton et al. (1975) used explosive blasts, the waveform could be approximated by a Friedlander waveform with zero rise time (i.e., b = 0 in the above equation), and P_{pk} and c equal to the peak pressure and time duration of the impulse, respectively, from their data as reported for each trial. The results of this model based on the data reported by Yelverton et al. (1975) for both 50% mortality and the no injury are shown in Figures A1 (page 76) and A2 (page 76).

To estimate the SEL values plotted in Figure 8 (page 72) for each of these cases, P(t) was calculate at the same time intervals used to record the pile driving waveform data and then summed to estimate the cumulative pressure squared values for each of the modeled waveforms in the graphs shown above. These SEL values were then calculated just as they were for pile driving waveforms. Thus each curve in Figures A1 and A2 corresponds to a single point plotted in Figure 8. Thus the SELs estimated in this way from Yelverton et al. (1975) data can be compared to SEL values calculated for actual pile driving waveforms recorded in the water to estimate their potential to cause injury or mortality to fish with a single impact. Appendix B provides information on application of the recommendations for interim guidance to multiple pile driving impacts.

The models described here can be applied to other impulsive or transient data associated with injury or mortality in fish to provide an estimate of SEL for the observed effect. This could be used for interim guidance until more research is completed.

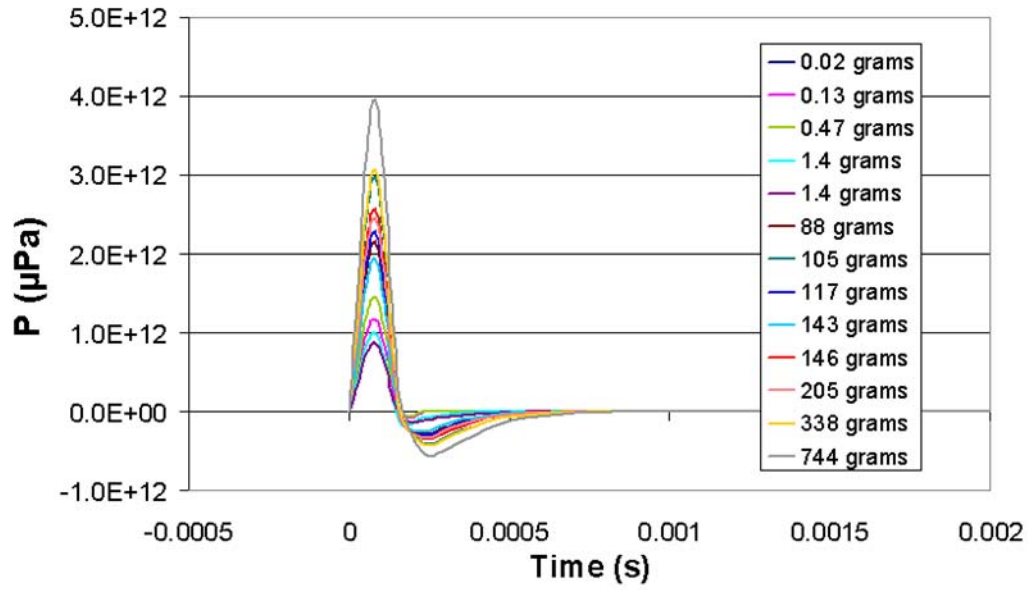

Figure A1: Modeled impulse waveforms resulting in 50% mortality for fish of different sizes based on data of Yelverton et al. (1975).

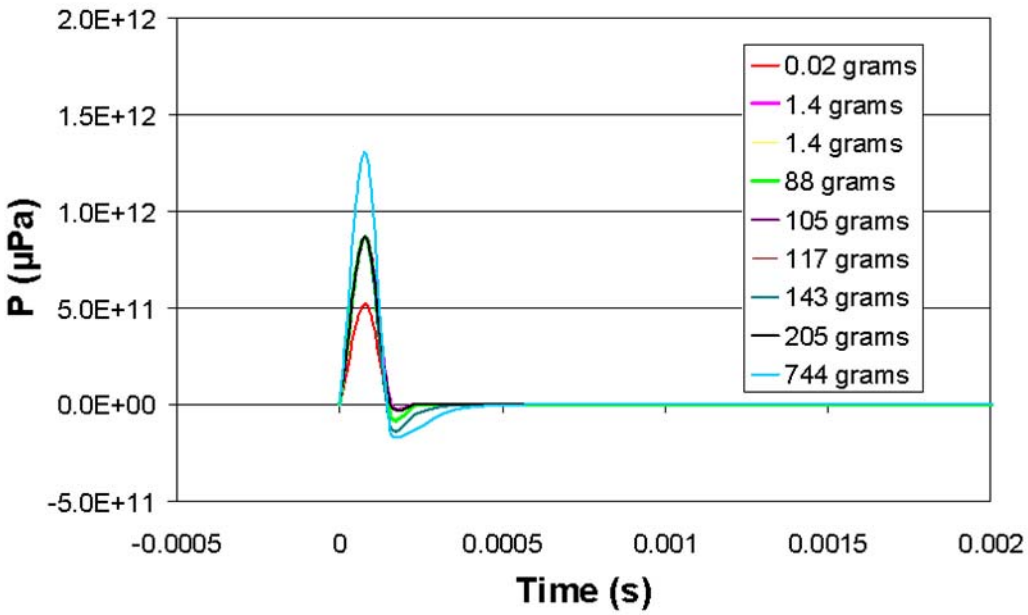

Figure A2: Modeled impulse waveforms resulting in no injury for fish of different sizes based on data of Yelverton et al. (1975).

Appendix B (Revised)

Comparison of SEL-Based Recommendations for Guidance with Available Data

A. Characteristics of Pile Driving Signals and Known Effects of Exposure

Different piles are driven with different types of hammers and in different types of environments, resulting in different sound levels. Table B1 provides a brief summary of numerous measurements in the San Francisco Bay Area (Reyff 2004; Rodkin, personal communication). Large diameter cast in steel shell (CISS) piles driven with impact hydraulic hammers clearly result in the greatest sound exposure. Timber piles that are driven with relatively small hammers produce relatively low amplitude sound pressure levels of less than 180 dB re 1 µPa (peak) at 10 meters from the pile. Concrete piles produce peak sound pressures of about 188 dB re 1 µPa, also at 10 meters from the pile. The larger CISS piles (i.e., 30-inch diameter or greater) produce much greater sound pressures. For instance, 30-inch diameter CISS piles driven with a diesel impact hammer produce 208 dB re 1 µPa (peak) at 10 meters from the pile and very large (96-inch diameter) CISS piles produce levels in excess of 220 dB re 1 µPa (peak) within 10 meters of the pile. Close to CISS piles, the RMS (impulse) is typically about 10 to 15 dB lower than the peak and the SEL is about 24 to 28 dB lower than the peak. These levels, however, are dependent not only on the pile and hammer characteristics, but also on the geometry and boundaries of the surrounding underwater environment.

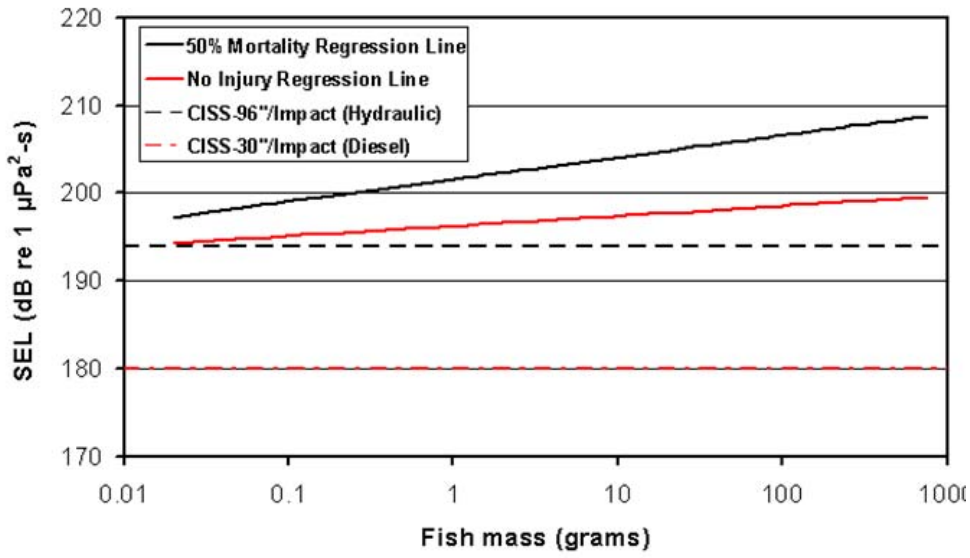

Figure B1: Comparison of received SEL at 10 meters with the recommended guidance for physical injury and 50% mortality from exposure to a single pile driving impact.

Figure B1 shows how SEL for a single impact measured at 10 meters from both a 30-inch CISS pile driven by a diesel impact hammer and a 96-inch CISS pile driven by a hydraulic impact hammer, compare with the recommended guidance for injury and 50% mortality displayed in Figure 8 (page 72). Comparison of the recommended guidance with pile

installations in the SFOBB area (Table B1) indicates that for single impacts, only very small fish having a mass of 1 gram or less, would be at high risk if located within five meters of pile driving that produces the highest sound levels – a 96-inch CISS pile being driven by a hydraulic impact hammer.

Table B1: Summary of Measured Underwater Sound Levels Near Marine Pile Driving

Pile Type	Distance from Pile (m)	Peak Pressure (dB re 1 µPa)	RMS(impulse) Pressure (dB re 1 µPa)	SEL (dB re 1 µPa^2-s)
--Various Projects				
Timber (12-in) Drop	10	177	165	157
CISS (12-in) Drop	10	177	165	152
Concrete (24-in) Impact (diesel)	10	188	176	166
Steel H-Type Impact (diesel)	10	190	175	--
CISS (12-in) Impact (diesel)	10	190	180	165
CISS (24-in) Impact (diesel)	10	203	190	178
CISS (30-in) Impact (diesel)	10	208	192	180
--Richmond-San Rafael Bridge				
CISS (66-in) Impact (diesel)	4	219	202	--
CISS (66-in) Impact (diesel)	10	210	195	--
CISS (66-in) Impact (diesel)	20	204	189	--
--Benicia-Martinez Bridge				
CISS (96-in) Impact (Hydraulic)	5	227	215	201
CISS (96-in) Impact (Hydraulic)	10	220	205	194
CISS (96-in) Impact (Hydraulic)	20	214	203	190
--SFOBB East Span				
CISS (96-in) Impact (Hydraulic)	25	212	198	188
CISS (96-in) Impact (Hydraulic)	50	212	197	188
CISS (96-in) Impact (Hydraulic)	100	204	192	180

To date, only one study has reported received SEL levels along with effects of exposure to pile driving signals (Caltrans 2004). The SEL's recorded in this study ranged from 158 to 182 dB (re 1 µPa^2-s) and were recorded at distances of 23 to 314 meters from the pile. These values are in the same range (or lower) as shown in Table B1 and Figure B1. In this study caged steelhead and shiner surfperch were exposed to pile driving sounds. The steelhead had standard body lengths of 6.5 to 22.7 centimeters with masses ranging from 26 to 177 grams. The shiner surfperch ranged in length from 5.6 to 10.5 centimeters, but their mass was not reported. Except for one anomaly, this study showed no statistically significant mortality (i.e. different than control groups) for SEL's as high as 181 dB (re 1 µPa^2-s) for surfperch and SEL's as high as 182 dB (re 1 µPa^2-s) for steelhead. In one trial 31% mortality occurred in surfperch at an SEL of 180 dB (re 1 µPa^2-s), while mortality in control groups was as high as 13.3%. The authors indicated that this anomaly might be attributed to a relatively large negative pressure occurring at the beginning of the waveform; however, there were no mortalities in other trials having the same large initial negative pressure (and SEL). The cause of this anomaly is most likely the poor handling of the test specimens and incomplete pathological analysis. Moreover, in this study physical injuries were not reported in a way that could be correlated with SEL measurements.

B. Characteristics of Explosive Blast Signals and Known Effects of Exposure

Most injury and mortality effects data on aquatic animals reported in the literature are from studies of explosive blasts. In these studies, injury and mortality data are from a single explosion. These waveforms typically have peak pressures several orders of magnitude above that of pile driving signals, as well as much faster rise and fall times, and consist of multiple oscillations between positive and negative pressures. The literature is in agreement that not peak pressure, but that some measure of how the acoustic pressure acts over time correlates with physical injury and mortality in fishes, and that fishes with swim bladders and/or other gas-filled chambers are most susceptible to harm. However, if the rise time is fast enough and/or peak pressure high enough, then the exposure will be fatal. Until recently, most studies about the effects of explosive blasts reported in the literature considered only the lethal values of peak overpressure.

Rasmussen (1967) noted that fish could withstand higher peak pressure from a gunpowder explosion than from a dynamite explosion because of the "more rounded front" of the pressure wave. He stated that the mortality limit for fish was 2.8 – 5.0 kg/cm^2 (229 – 234 dB_{peak} re 1 µPa) for dynamite explosions, but increased to 8.5 – 11.0 kg/ cm^2 (238 – 241 dB_{peak} re 1 µPa) for gunpowder explosions. Trasky (1976) reported similar values: lethal peak overpressures of 40 –50 psi (229 – 231 dB_{peak} re 1 µPa) for dynamite and 124 –160 psi (238 – 241 dB_{peak} re 1 µPa) for gunpowder explosions. Because early studies of injury and mortality reported only peak pressure, there is conflicting information in the literature as little or nothing is known about the temporal characteristics of the waveform. For example, Trasky (1976) indicated that salmon and herring fry (3-6 months old) are killed by peak over pressures of 2.7 psi (205 dB_{peak} re 1 µPa), while Govoni et al. (2003) found that it took an average maximum pressure of 636.92 kPa (236 dB_{peak} re 1 µPa) to mortally injure juvenile pinfish and spot. Because pile-driving signals have slower rise and fall times than those generated from dynamite blasts, a lethal peak overpressure for a single exposure to a pile driving impact should be on the order of that reported for black gun powder or even higher (i.e., greater than about 240 dB_{peak} re 1 µPa).

More recent studies have shown that the energy flux density ($E_f = \int \boldsymbol{pv}\, dt$)[14] is a good predictor of damage to fish for explosive blasts. For 50% mortality, the lethal E_f is reported to be 300 joules per square meter (J/m^2) (e.g., Sakaguchi et al. 1976; Wright 1982). The energy flux density reported in these studies, however, is actually the sound exposure, $\int p^2\, dt$, divided by a constant as explained in the next paragraph. So it is proportional to SEL and not the true energy flux density unless the experiment occurred in an unbounded region. This is rarely the case because of interference from the water surface and sea bottom, as well as other surfaces in the water (e.g., piers, boats, barges, buoys, coral, animals, etc.).

Weston (1960) provided a detailed description of the acoustics of underwater explosions. He indicated that the energy flux density must be used to quantify acoustic pulses produced by explosions as this quantity obeys the same transmission laws as intensity ($\boldsymbol{I} = p\boldsymbol{v}$) does for continuous-wave sources. As he pointed out, however, in practice the quantities that are usually measured are sound pressure and time. So the true energy flux density, $\int \boldsymbol{pv}\, dt$, is rarely

[14] Bold type indicates that the variable is a vector, which has both magnitude and direction.

determined because it requires measurement or a good estimate of the acoustic particle velocity, ***v***. Instead researchers have assumed that the explosive wave is a plane wave or a spherically symmetric wave (i.e., propagating radially outward in all directions from the source), which has a defined relationship between acoustic pressure and particle velocity: $v = p/\rho c$, where ρ is the water density, c is sound speed in the water, and the bold type for v is no longer necessary because plane waves and spherically symmetric waves propagate only in one direction. Using this relationship the energy flux density is $E_f = (1/\rho c) \int p^2 \, dt$ and the constant $(1/\rho c)$ will change with water temperature, salinity, and depth (pressure). Figure B2 shows how the lethal limit, E_f = 300 J/m^2, compares with the recommended guidance based on SEL, assuming that $\rho c \approx 1.6 \times 10^6$ for seawater. The energy flux lethal limit and the recommended guidance are both derived from explosive blast effects data. Thus because pile driving signals have smaller peak pressure amplitudes and slower rise and fall times than blast waveforms, both provide conservative guidance for exposure to a single pile driving impact.

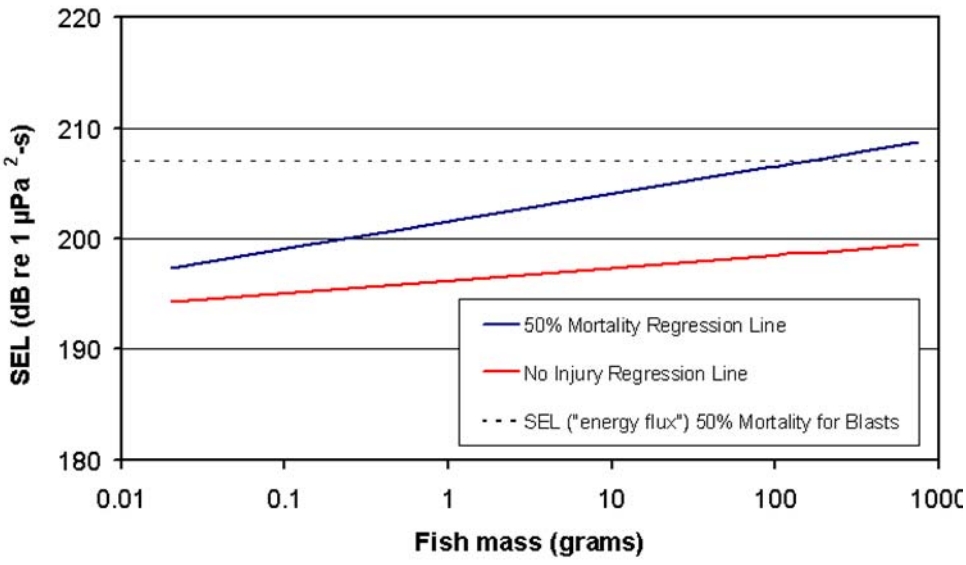

Figure B2: Comparison of lethal energy flux (50% mortality) reported in the literature with the recommended guidance for physical injury and 50% mortality. Both are derived from explosive blast effects data on fish and therefore should be conservative for exposure to a single pile driving impact.

Hempen and Keevin (1995) and Keevin and Hempen (1997) report results of a study conducted by the U.S. Army Corps of Engineers in 1992, to determine the effects of explosive blasts in shallow water on bluegill (*Lepomis macrochirus*) having an average mass of 40 grams (40 g). They determined percent mortality by grading internal injury via pathology and histology examinations based on Hubbs and Rechnitzer (1952). This type of examination could result in an overestimation of mortality. In addition, because the tests were in shallow water, the true energy flux densities will be higher than those reported using $E_f = (1/\rho c) \int p^2 \, dt$ because the actual acoustic particle velocity will be higher than that for a plane or spherically spreading wave. Nevertheless, Figure B3 shows their data for two different trials using the fresh water constant, $\rho c \approx 1.5 \times 10^6$, to estimate SEL from their reported values for energy flux density. The actual values of energy flux density would be higher than indicated by the estimated SEL. These

results show that both acoustic particle velocity and pressure should be measured to determine the true energy flux density acting on fishes in a complex acoustic field.

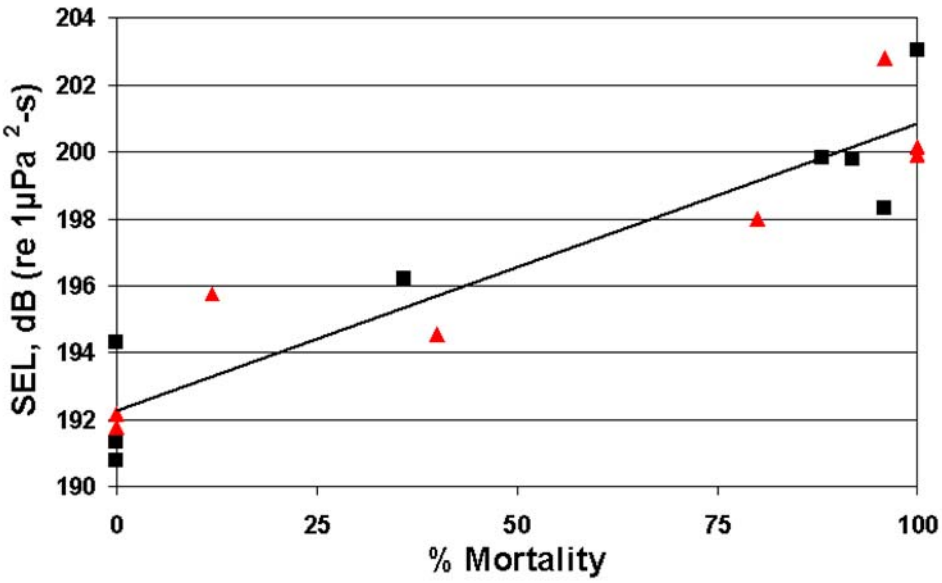

Figure B3: Percent mortality for bluegill (40 g average mass) correlated with SEL estimated from values of energy flux density (i.e., SEL) reported by Hempen and Keevin (1995). These data indicate 50% mortality about 7 dB lower than the recommended guidance for a single exposure to a pile-driving impact. However, because these experiments were done in shallow water, the true energy flux density is expected to be higher than reported. (■ Trial 1; ▲ Trial 2)

C. Application of Recommendations for Interim Guidance to Multiple Pile Driving Impacts

The recommendations for interim guidance to protect fish from physical injury and mortality given by the curves in Figure 8 can be related to effects data from continuous wave exposure studies by estimating the energy exposure in Joules per square meter (J/m^2) from the acoustic intensity [watts per square meter, $W/m^2 = J/(s\text{-}m^2)$] and duration of the sound exposure, and equating it to E_f. Moreover if sound exposure ($\int p^2\,dt$) from a single pile-driving strike is known, it can be summed to estimate the cumulative energy exposure from multiple strikes, which can then be compared to the curves in Figure 8. Some recovery of the tissue will take place during the interval between strikes that is not taken into account, so this approach should be conservative.

Alternatively, if the sound intensity or energy exposure for an observed effect is known, a safe SEL per strike can be estimated by using the pressure-particle velocity relationships for a plane wave. As an example, the energy exposures for Hastings (1995) "worst case" injury and mortality were estimated. The worst cases were for 3- to 4-inch long blue gouramis (*Trichogaster trichopterus*) with a mass of 10-15 grams. One was stunned (i.e., became unconscious) after only 10 minutes exposure and others died after only 30 minutes exposure

(50% mortality based on 6 fish), both to a 400-Hz tone at 192 dB re 1 µPa (peak). In contrast, the worst case (25% mortality based on 12 fish) for 6-inch long goldfish, about 100 grams each, was mortality after a one-hour exposure to 204 dB re 1 µPa (peak) at 250 Hz.

The waveguide used by Hastings (1995) was a Plexiglas tube flanged to a Naval Research Labs J13 underwater sound projector on one end and covered with a rubber cap on the other. The rubber cap had approximately the same acoustic impedance as water, so it was quivalent to a water-air interface. The sound field inside the tube was a standing wave and particle velocity over the length of the tube was calculated for each test frequency using measured pressure values. Then the sound energy doses for these cases were estimated by calculating the acoustic energy densities for each exposure and assuming that the energy could move at the sound speed inside the waveguide. The first two columns of Table B2 summarize the results of these calculations.

To compare an energy dose or energy flux density, E_f, in J/ m^2 with an allowable SEL, one must use approximations for a plane wave. Then the relationship between sound pressure (p) and particle velocity (v) is $p = (\rho c)v$, where ρ (kg/m^3) is the density of the fluid and c (m/s) is the speed of sound in the fluid. The product, ρc is called the characteristic impedance and its value is about 1.6×10^6 (kg/m^2-s) for seawater and 1.5×10^6 (kg/m^2-s) for freshwater. Using these values an allowable SEL for each hammer impact can be calculated for a given number of pile strikes as follows:

$$\text{SEL per Strike} = 10 \log [\rho c \, E_f / 10^{-12} / (\#\text{ strikes})]$$

This approximation was used to calculate the SEL per strike for two different scenarios that would give an equivalent sound energy dose in seawater as shown in the last two columns of Table B2. The third column gives the equivalent SEL for a single strike for each condition. Comparison of these equivalent single-strike SEL's with Figures 8 and B2 (above) shows that the recommended guidance is conservative based on the worst-case data for injury and mortality from Hastings (1995). This is to be expected because the recommended guidance is based on exposure to blast waves, which have much higher peak pressures and much faster rise and fall times than do either pile-driving waveforms or the 250- and 400-Hz continuous wave signals used by Hastings (1995). It is important to note that rise and fall times in 250-500 Hz continuous wave signals are about the same as those of pile-driving signals generated by striking CISS piles.

Table B2: Relating Energy Dose Data to Multiple Pile Driving Strikes

Condition	Estimated Sound Energy Dose, E_f (J/m^2)	Equivalent Single-Strike SEL for direct comparison with Fig. 8 (dB re 1 µPa^2-s)	SEL per Strike for 1800 strikes (dB re 1 µPa^2-s)	SEL per strike for 3600 strikes (dB re 1 µPa^2-s)
Gourami (10-15 g) unconscious/10 min. (Hastings 1995)	6910	220	188	185
Gourami (10-15 g) killed/30 min. (Hastings 1995)	21,000	225	193	190
Goldfish (100 g) killed/60 min. (Hastings 1995)	13,680,000	253	221	218