BLASTING EFFECTS ON SALMONIDS

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Prepared for the Alaska Department of Fish & Game
Division of Habitat

June 2013

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FINAL REPORT

by

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Prepared for the Alaska Department of Fish & Game
Under Agency Contract IHP-13-051

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June 2013

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SUMMARY

In 1991 the Alaska Department of Fish and Game developed guidelines to protect fish and incubating embryos from the impacts of blasting in and near water bodies. The guidelines established that blast induced pressures should not exceed 2.7 psi (lbs/in^2, 19 kPa) in the water and vibrations should not exceed 0.5 in/s (13 mm/s) in spawning gravels when fish or embryos are present. The ADFG Division of Habitat is in the process of revising this standard to reflect recent research and technological advances and a better understanding of blasting impacts on fish. Specifically, resource managers would like to identify the effects of blasting and the levels of pressure and vibration that cause injury to fish and embryos. The physiological effects of mechanical shock and blast induced vibrations on embryos and of blast induced overpressures on fish are described below. The results of three empirical studies examining the tolerances of salmonid embryos to mechanical shock exposure suggest that 5.8 in/s (147 mm/s) is the minimum particle velocity that causes negative effects. The results of several investigations that exposed caged fish to blast induced overpressures of known values indicate that the lowest measured overpressure to cause injury to salmonid species is 10.0 psi (69 kPa).

1.0 INTRODUCTION

Projects involving pile driving, blasting, and seismic exploration in the State of Alaska often occur in close proximity to aquatic organisms. These activities can introduce sound into the environment above ambient levels that can impact species and their habitats. The Alaska Department of Fish and Game (ADFG) issues permits for certain activities occurring in rivers and streams known to support anadromous and resident fish species. The *ADFG Blasting Standards for the Protection of Fish* (1991) state that

> "*…no person may discharge an explosive that produces or is likely to produce an instantaneous pressure change greater than 2.7 pounds per square inch (psi) in the swim bladder of a fish or produces or is likely to produce a peak particle velocity greater than 0.5 inches per second (in/s) in a spawning bed during the early stage of egg incubation.*"

The *ADFG Blasting Standards for the Protection of Fish* (1991) were developed to assist ADFG in permitting sustainable development based on a review of available information at the time. Since that time, new information from recent scientific studies has provided additional insights to justify revisiting the Standards.

The purpose of this report is to provide ADFG resource managers a summary of relevant literature to assist them in revising and updating blasting guidelines for the protection of salmonid species from the impacts of blasting. The paper is organized to provide a review of blasting principals and monitoring of blast-induced vibrations and overpressures. Common injuries associated with impulsive sounds are explained. A review of studies that correlate blast pressure with measured effects on salmonids is given.

2.0 BLASTING AND EXPLOSIVES

The Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF) categorizes explosives as low explosives, high explosives, and blasting agents. Low explosives include slow burning black powder and pyrotechnics. Most construction and seismic work utilize high explosives and blasting agents placed in blast holes drilled in rock that detonate at much higher velocities than low explosives. During the detonation of explosives, a rapid chemical reaction occurs that produces pressure, heat, and gas products. The detonation pressure forms a shock front resulting in rock fragmentation, displacement, air overpressure, ground vibration, and water overpressure (ISEE 2011). The detonation process is followed by a rapid expansion of gas products that occupy hundreds of times more volume than the undetonated explosive materials. The rapid gas expansion creates a secondary pressure pulse that decays far slower than the detonation shock pulse. More information on explosive types can be found on the Institute of Maker Explosives (IME) website (www.ime.org) or at the International Society of Explosives (ISEE) Engineers website (www.isee.org).

The use of explosive in or near bodies of water can include demolition work or road and bridge work. Demolition of structures generally involves open-air explosives that may impact bodies of water in the form of air overpressures or sound pressure. Road and bridge works involves excavating rock using buried explosives charges that are well-coupled into the ground subsurface. This form of "dry" blasting can impact near-by bodies of water by the lateral transfer of ground vibrations along the water edge to create water overpressures. Land-based ground vibrations can enter into the substrate and propagate as particle motions along the water-substrate interface.

Explosives are further used in underwater or "wet" blasting to excavate rock on the bottom of rivers, lake and in marine environments. In this application, water overpressures from detonation and gas expansion pulse the water in a complex manner throughout the water column.

2.1 SUBSTRATE VIBRATIONS

Blast energy travels through the ground as particle motion and is characterized in terms of amplitude or intensity, duration, and frequency (f, in Hertz, Hz). Ground vibrations, in terms of velocity, is measured using tri-axial geophones well-coupled in the ground.

Measurements are reported as peak particle velocity (PPV, in in/s, mm/s). PPV is the highest amplitude in any one of the three components of motion as measured by a tri-axial geophone.

In some cases, maximum displacement (D, in inches or millimeters, mm) or acceleration (A, in in/s^2, g's, or mm/s^2) is required for analysis and each may be computed from PPV and frequency at the PPV (f). The formulas used assume the characteristic waveforms at the maximum values are close to a sinusoid.

$$A_{max} = 2\pi f\,(PPV)$$

$$D_{max} = (PPV)/2\pi f$$

Accurate vibration measurement of the substrate requires that a waterproof geophone is well-coupled within the substrate.

2.2 WATER OVERPRESSURES

Water overpressure is the sudden change in water pressure from ambient pressure caused by an underwater explosion. Underwater explosions can be classified as unconfined and confined. Unconfined explosions describe detonation of explosives that are not enclosed within a drill or bore hole and are rarely, if at all, used in construction. An example of an unconfined explosion would be the detonation of an explosive in mid-water or resting on the surface bottom substrates. These conditions that describe a large open body of water with only surface and bottom boundaries from which pressure waves reflect are termed 'free-field' conditions. Free-field conditions are the basis of theoretical equations describing underwater explosions. (Simmonds and MacLennan 2005).

When an unconfined explosion is detonated underwater, a high amount of energy moves away from the blast center in the form of a shock front and spreads in all directions. A rapidly expanding bubble of gas sharply increases pressure at the bubble's surface until inertia of the surrounding water and elastic properties of gas cause the bubble to contract reducing the pressure at the bubble's surface to less than ambient levels. The bubble size continues to oscillate in free-field conditions creating a pulse between positive and negative pressures (Cole 1948). An example of an unconfined detonation is shown in Figure 1.

When an explosive is confined within bedrock beneath a water body to fragment and excavate rock, explosive charges within drilled holes are laid out in a grid and each blast hole is donated on a unique millisecond (ms) time-delay. The blast pulse the rock-water interface in a complex series of positive and negative pressure peaks as measured within the water column and shown in Figure 2.

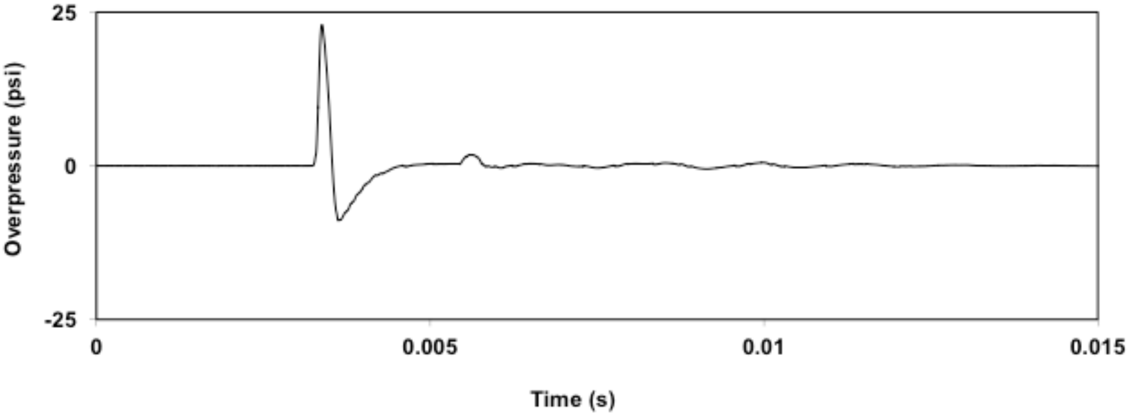

Figure 1. Example of a pressure-time recording of a single detonation source in open water

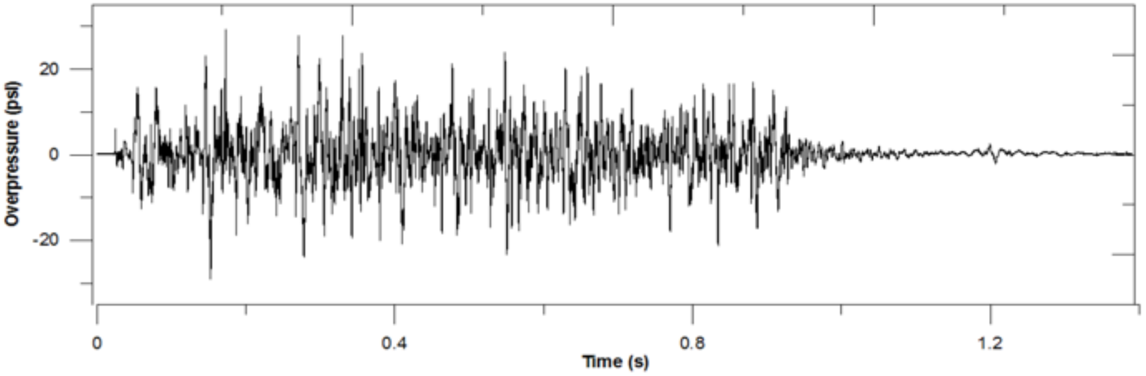

Figure 2. Pressure-time history for well-coupled, buried explosive charges drilled into the bottom of a river

Surface and bottom boundaries reflect pressure waves and can create these complex waves in shallow water conditions. When a positive pressure wave reaches the water surface, there is insufficient atmospheric pressure to resist the pressure, and the energy is reflected as a negative phase opposite of the direct wave. The reflected surface wave can combine with the rarefaction portion of the direct wave (such as the tensile component shown in Figure 1) and cause large rarefactions (negative pressures) (Cole 1948). Waves reflected from the bottom have positive pressure fronts and travel slower than surface reflected waves. As such, measured water overpressures along the water bottom may be far lower in amplitude that pressures measured higher in the water column.

When an explosion occurs in free-field conditions and the resulting wave propagates far without boundary effects, empirical equations can be applied to predict parameters that describe attenuation in the pressure-time waveform (Cole 1948). However, equations based on free-field conditions cannot be used to predict pressure parameters when several boundary reflections are present (Simmonds and MacLennan 2005) or when explosives are confined in rock or other materials that create longer duration pressure waves (Munday et al. 1986). Other physical factors such as water temperature and density can affect the shape of the pressure time-history once the shock pulse has been reduced to normal acoustic intensity in which the speed of sound in water is 4,921 to 5,053 ft/s (1,500 to 1,540 m/s) (Cole 1948).

The pressure-time signature recorded from an explosion can be separated into two parts. The first contains a near instantaneous rise to a maximum peak pressure caused by detonation followed by an exponential decay to a minimum pressure. The second part of part of the wave is caused by the more slowly occurring chemical reaction of the explosion forming gas products. The entire process takes place in milliseconds.

Blast strength from the pressure-time history can be measured and reported in several ways in terms of average, peak, summations, and impulse levels. Several studies have attempted to correlate explosives source energy with distance away from the detonation point and fish injury (Yelverton et al. 1975, Munday et al. 1986, Goertner et al. 1994, Carlson et al. 2011). Peak pressure and impulse are the most commonly reported parameters in most studies.

2.2.1 Sound Pressure Level

Peak sound pressure level (SPL_{peak}) is the highest amplitude in the pressure-time history and is commonly reported in pounds per square inch (psi) or Pascals (Pa). Peak pressure can be calculated many ways including the absolute maximum pressure (independent of phase), zero-to-peak (where the peak or maximum value is either positive or negative), peak-to-peak, and positive or negative peak values. If the peak has been log transformed to $SPL_{peak,}$ it is reported in decibels (dB) and the appropriate reference unit for water is 1μPa. Thus the peak is reported as dB re 1μPa.

2.2.2 Impulse

Impulse (I) is the integral of the pressure-time waveform and is calculated over a time interval.

$$I = \int_{t_1}^{t_2} P \, dt$$

Impulse values are typically reported in units of psi•msec or Pa•msec. Bar•msec are also used, as the bar is equal to 100,000 Pascals, which is approximately the atmospheric pressure on Earth at sea level.

No one method is used to calculate impulse strength. Impulse, which is the area under the pressure-time curve, has been reported for a single peak, either positive or negative, or as the average over the entire time-history. Cole (1948) identified the problem of establishing an upper time limit for integration as the selection of t_2 can greatly influence the impulse reported.

Explosions in open water create a short-lived transient pressure and impulse strengths can be influenced by long-term pressure responses included in the calculation. As such, the exact method of calculating impulse is important when comparing study results. Confined blasts have a longer positive pressure phase than unconfined open water shots which could create elevated impulse values making comparison difficult. Specifically, it is important to know the time interval used and which components of the shock wave were integrated (i.e. initial pulse, subsequent reflections, positive only, negative only, etc.). Other factors that have been found to influence the final impulse strength calculation include the frequency response of measurement system (Munday et al. 1986).

Some researchers have found that impulse correlated better with fish injury than peak pressures (Yelverton et al. 1975) and others have reported peak pressure as the strongest correlating parameter (Houghton and Munday 1987, Carlson et al. 2011). Gaspin et al. (1976) reported that impulse predicted mortality better only at depths less than 9.8 ft (3 m) and others have stated that impulse was not a good predictor of damage for confined charges (Munday et al. 1986). Clearly there is no agreement as to the blasting impact parameter that best describe injury to fish.

2.2.3 Energy flux

Energy flux density is the rate of energy flow through a unit surface area (Wright 1982) and has been scarcely studied or referenced in regards to blast effects on fish. Baxter et al. (1982) used energy flux density to predict fish mortality based on weight. Current literature suggests that energy flux density only be used at great depths since it does not account for surface pressure release (Simmonds and MacLennan 2005).

2.2.4 Measuring and recording water overpressures

Blast pressures are measured with passive transducers that convert energy from one form to another and allow continuous measurement of pressure fluctuations as a function of time. A hydrophone is a type of electroacoustic transducer that converts acoustic energy to electric energy. Two types of hydrophones commonly used to measure blast pressures are piezoelectric and electrorestrictive. Piezoelectric transducers consist of a crystal (i.e. quartz or tourmaline) element in a fluid-filled tube. Electrorestrictive transducers are made from relatively inexpensive piezoceramic materials that can be molded into various shapes. Both types of hydrophones convert pressure changes into electrical signals that can be recorded and viewed as a function of time.

Pressure-time measurements made by transducers are recorded with data acquisition systems. Today most systems are digital but in the past analog recordings were made through the use of oscilloscopes. Signal conditioners and voltage amplifiers may also be incorporated into pressure monitoring systems if necessary.

2.3 SCALED DISTANCE ATTENUATIONS

Scaled distance is a means of incorporating the two most important factors contributing to the intensity of ground motion and overpressures: source energy and distance. Source energy is the maximum charge weight detonated per 8-millisecond delay and distance describes the shot-to-seismograph distance. Square-root scaled distance (SRSD) is used as the scaling parameter in measuring ground vibration and cube-root scaled distance (CRSD) is used for scaling steep-fronted compression waves at a distance and is most common for air and water overpressure measurements (Siskind 2000). The scaled distance relationships for ground motion and for water overpressure are shown in the following equations.

$$SRSD = \frac{\text{distance}}{\sqrt{\text{charge weight}}}, \frac{\text{ft}}{\text{lb}^{1/2}}$$

$$CRSD = \frac{\text{distance}}{\sqrt[3]{\text{charge weight}}}, \frac{\text{ft}}{\text{lb}^{1/3}}$$

where SRSD is square-root scaled distance that applies to ground motions and CRSD is cube-root scaled distance that applies to underwater pressure. Calculated values of scaled distance are plotted against measured PPVs or SPL_{peak} values to develop site-specific attenuation models that describe the rate of motion of pressure decay as a function of distance at a particular blast site. The best-fit equations describing ground vibration and pressure attenuation take on the forms

$$PPV = a * SRSD^{-b}$$

$$SPL_{peak} = a * CRSD^{-b}$$

where ‘a’ is the y-intercept value at scaled distance =1 and ‘b’ is the attenuation exponent that describes the rate of decay in PPV or SPL. The parameter ‘a’ is the energy term that represents the relative magnitude of explosive energy coupled into the ground at the blast site and dependent on explosives type and rock quality. The attenuation slope term ‘b’ is a function of geology transmitting the energy between the blast site and the seismograph.

Site-specific attenuations are used to predict ground vibration and overpressures at selected distances from blasting operations and can be useful in determining ranges of effects on structures and species. An example of an attenuation plot is shown in Figure 3.

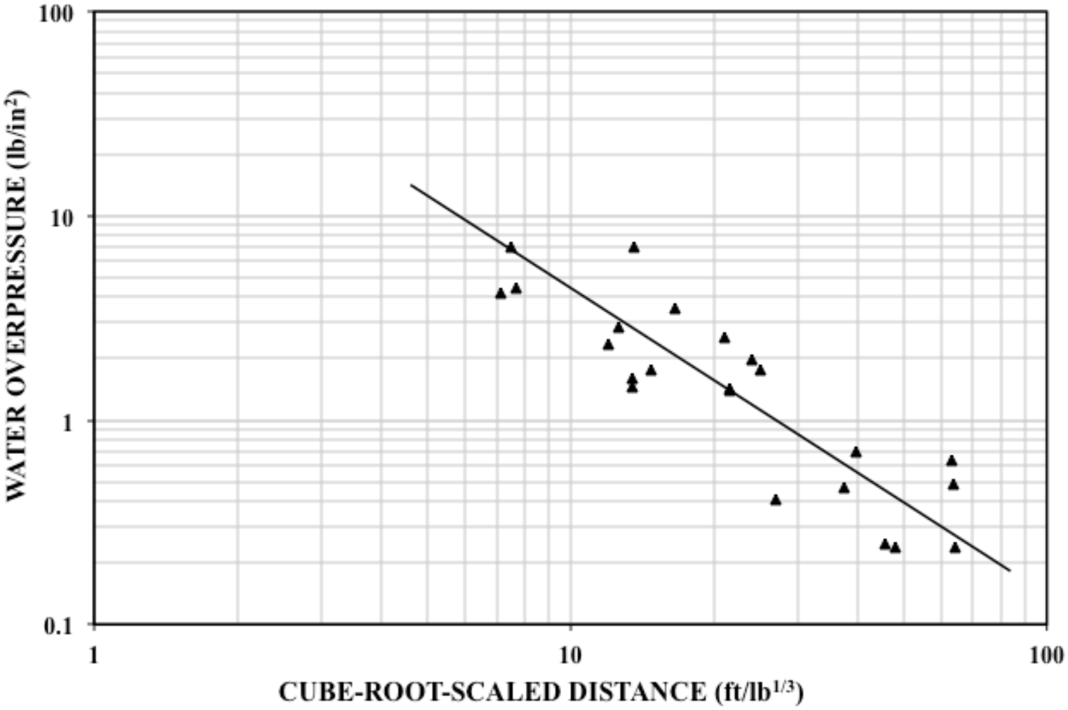

Figure 3. Example of scaled distance attenuation. Data points represent blast overpressures at distances scaled by maximum charge weight per delay

3.0 EFFECTS OF BLASTING AND MECHANICAL SHOCK ON EMBRYOS

3.1 EMBRYONIC DEVELOPMENT AND PHYSICAL SHOCK

Embryonic development begins when an egg is fertilized and the time until hatching is largely determined by water temperature. Warmer water increases developmental rate and metabolism. Temperature units (TUs) are used to describe developmental stages and are defined as the number of days multiplied by the temperature above zero in Celsius. Embryo sensitivity to shock varies throughout development. Most salmonid embryos are relatively resistant to shock immediately after fertilization until epiboly begins around 50 TUs (i.e. 5 days at 10 degrees C). During early epiboly the germ ring, which will later become the body wall, begins to cover the yolk mass. By late epiboly (around 140 TUs) the exposed portion of the yolk mass, termed the blastoderm, is nearly covered. During epiboly embryos are highly sensitive to physical shock. After this stage the yolk plug is closed and embryos become more tolerant to physical shock (Smirnov 1955, Jensen and Alderdice 1983, Faulkner et al. 2008). Eye pigmentation can be seen externally at approximately 270 TUs and most hatching occurs around 500 TUs (Velsen 1980, Quinn 2005).

Embryos exposed to physical shock during epiboly can sustain tears in the perivitelline membrane causing yolk to leak within the embryo (Smirnov 1954). Sixteen species of embryos exposed to mechanical shock from an air gun, electric pulse generator, or TNT exhibited injuries including severe deformation of the embryo and yolk mass, and depression of the membrane into the egg (Kostyuchenko 1973). Godard et al. (2008) measured cranial widths for potential disruptions in eyed embryos exposed to seismic blasting.

3.2 EMPIRICAL STUDY RESULTS

Tolerance to physical shock has been tested in many ways from dropping, to squeezing and vigorously shaking embryos (Quinn 2005). Mechanical shock devices were developed to expose embryos to abrupt physical shock in an effort to simulate transient impulse vibrations similar to those from blasting. Three studies that examined mechanical shock tolerances and effects on salmonid embryos are summarized below.

Jensen 2003, Jensen and Alderdice 1989

The purpose of this study was to confirm that the Canadian Department of Fisheries and Oceans (DFO) established criteria of 0.5 in/s (1.3 cm/s) was sufficient for the protection of salmonid eggs. Jensen (2003) converted data collected in an earlier study (Jensen and Alderdice 1989) from units of energy (ergs; gram•cm^2/sec^2) to velocities. The original study used a mechanical shock device that consisted of a metal carrier that held a petri dish containing a single layer of eggs. When a release was triggered, the carrier released from an adjustable height platform and fell freely until impact. The petri dish and carrier were designed not to bounce. Six species of salmonids were exposed to three different drop heights and tests were repeated at each interval with 20 to 30 eggs per trial. Embryo sensitivity to mechanical shock was examined at various development stages. Basic physical principles were used to calculate the acceleration and velocity of eggs dropped from various heights. Jensen and Alderdice (1989) showed that egg sensitivity increased soon after fertilization and that eggs became extremely sensitive to shock during epiboly. Jensen (2003) compared velocity thresholds to PPV criteria recommended by Wright and Hopky (1998) and concluded that the current DFO guideline criteria of 0.5 in/s (13 mm/s) provided at least a ten-fold margin of protection for Pacific salmon eggs during their most sensitive life stages. A table of the results is shown in Table 1.

Table 1. Mechanical drop test results (Jensen 2003). Predicted minimum velocities resulting in 10 percent mortality (Lethal Dose, LD10) based on mechanical drop test results and predictive model.

	LD10 Velocity	
Embryo species	in/s	mm/s
Chinook (*O. tshawytscha*)	5.8	147
coho (*O. kisutch*)	9.1	231
steelhead (*O. mykiss*)	13.1	333
chum (*O. keta*)	16.4	417
pink (*O. gorbuscha*)	24.5	622
sockeye (*O. nerka*)	33.0	838

Faulkner et al. 2006

Faulkner et al. (2006) exposed lake trout (*Salvelinus namaycush*) embryos to PPVs from open-pit-mining blasts conducted at the Diavvik Diamond Mine. Lake trout eggs were placed in 20 Plexiglas incubators each containing 50 eggs. Divers placed the incubators in September in lake substrate at 4 locations representative of native lake trout spawning sites at 9.8 to 16.4 ft (3 to 5 m) deep. Incubators allowed eggs exposure to natural conditions while protecting them from predation.

Some incubators were retrieved early after 20 days and exposure to six blasts. Most embryos had completed epiboly and were in the beginning stages organogenesis. The rest of the incubators could not be retrieved until ‘ice-out’ in mid-July. The late retrieval group had already hatched and specimens were classified either dead (eaten or decomposed) or alive (escaped). During the entire incubation period there were 96 blasting events, and measured PPVs exceeded (DFO) guideline criteria (0.5 in/s, 1.3 mm/s) more than 20 times. Blast induced vibrations were measured and recorded with an underwater geophone deployed at each incubator site and well-coupled to the lake substrate. Underwater overpressures were also measured and the highest SPL_{peak} was 0.002 psi (0.011 kPa).

There were no measureable effects of blasting during the early exposure period when eggs were most sensitive to physical shock. Blast vibrations did not exceed 0.05 in/s (1.3 mm/s) during this exposure. The highest PPV recorded over the entire incubation period was 1.1 in/s (28.5 mm/s) and mortality of exposed embryos was not significantly different than mortality amongst the control group.

Arctic ice was a major difficulty for this study. The longer exposure group could not be retrieved prior to the disappearance of ice; meaning that eggs hatched and fry were able to escape. Various escapement corrections were applied during analysis and none supported increased mortality in the exposure group when compared to the control.

Faulkner et al. 2008

Faulkner et al. (2008) related PPVs from simulated blasting to egg mortality. Rainbow trout (*Oncorhynchus mykiss*) eggs were subjected to laboratory simulated blast vibrations up to 9.7 in/s (245.4 mm/s). Simulations were carried out with a mechanical apparatus that dropped a weight from a desired height onto a steel plate. Embryos were held in a fiberglass tank coupled to the same steel plate. Vibrations were measured with a geophone coupled to the bottom of the tank. After exposure, all eggs were placed in an incubation tray to allow further development.

Six developmental stages were examined. Treatments included single and repeat exposures, and eggs held loose in-water versus eggs placed in spawning gravels. The investigators found that for single exposure embryos (for three developmental stages corresponding to early epiboly held in water), PPVs ranging from 0.5 to 8.6 in/s (12.4 to 219.3 mm/s) caused no significant difference in mortality between developmental stages or when compared to the control group. Repeat exposure trials also did not create a significant difference in mortality for magnitudes ranging from 1.4 to 9.7 in/s (36.3 to 245.4 mm/s). Spawning gravel effects were examined by exposing eggs in late stages of epiboly to repeat exposures from 1.4 to 9.7 in/s (36.3 to 245.4 mm/s). Increased mortality was observed among embryos in spawning gravels when compared to those held loose in-water. Embryos in spawning gravel exposed to 9.7 in/s (245.4 mm/s) exhibited significantly higher mortality than the control group. Mortality was also higher at 7.8 in/s (199.1 mm/s), however PPV exposures were not reliable. Exposures of 5.2 in/s (132.3 mm/s) showed no signs of increased mortality in the spawning gravel exposure group.

Faulkner et al. (2008) also examined the accuracy of the drop height method used by Jensen and Alderdice (1989) by constructing a mechanical drop apparatus similar to the one used in the original study. Exposures were conducted in and out of water for five developmental stages from early to late epiboly. Calculated velocities were similar to Jensen and Alderdice (1989) but mortality was not significantly different between developmental stages, in-water or out-of-water, or exposure and control groups.

Godard et al. 2008

Rainbow trout embryos were held in plastic bags filled with water and exposed in mid-water column to seismic charges detonated in the substrate of a frozen lake in Inuvik, Northwest Territory, Canada. Plastic bags were held in a mesh cage with attached hydrophones and exposed to 0, 9.3, 15.2, 33.1, and 40.6 psi (0, 64, 105, 228, and 280 kPa). Upon examination there were no significant differences between exposure and control groups. The details of this study are explained in the following section.

4.0 EFFECTS OF BLASTING ON FISH

Several species of fish have been exposed to blasting and effects have been observed as free-swimming mortalities, bird and gull predation, mid- and bottom-sampling trawls, and caged fish studies (Hubbs and Rechnizter 1952, Kearns and Boyd 1965, Teleki and Chamberlain 1978, Houghton and Munday 1987, Keevin and Hempen 1997, Carlson et al. 2011). The following section describes observed injuries associated with exposure to blast pressures.

4.1 BAROTRAUMA INJURIES

Barotrauma is the physical damage caused by quick changes from ambient pressure and can result from exposure to blasting, seismic air guns, hydro-turbines, or pile driving (Govoni et al. 2003, Popper et al. 2005, Stephenson et al. 2010, Halvorsen et al. 2012). Barotrauma injuries are assessed through gross anatomical examination and microscopic examination, or histopathology, of tissue.

Swim bladder

The swim bladder is the most commonly damaged organ in fish exposed to rapid pressure changes and is the cause of most internal barotrauma injuries (Yelverton et al. 1975, Goertner et al. 1994, Govoni et al. 2003). Fish tissue has a similar density to water, therefore a pressure wave travelling though water will pass relatively undisturbed through tissue until it contacts the swim bladder which is filled with gas. The swim bladder expands and contracts in response to the positive and negative phases of the pressure wave. Since tissues are more resistant to compressive rather than tensile forces, extreme negative pressures can more easily damage the swim bladder (Simmonds and MacLennan 2005) causing it to burst outward into the abdominal cavity (Christian 1973, Kearns and Boyd 1965). The degree of injury within the swim bladder can vary from over inflation, ruptures, tears and bruises. An expanding and contracting swim bladder can damage other organs, muscle and mesentery tissue, and can empty gas into the GI tract. Other reported injuries include ruptured and stretched tissue, hemorrhages, and hematomas in the swim bladder (Teleki and Chamberlain 1978, Govoni et al. 2003, Godard et al. 2008, Carlson et al. 2011).

Healing and recovery from swim bladder injuries has been observed under ideal conditions (Wiley et al. 1981, Yelverton et al. 1975, Casper et al. 2011) but may be more difficult in natural conditions. Fish with injured swim bladders may not be able to regulate buoyancy and could become more vulnerable to predation (Govoni et al. 2003).

Hemorrhage

Hemorrhaging can occur internally or externally and has been reported in several studies. The degree of hemorrhage can vary from non-lethal minor hemorrhaging in fins and epidermal tissue (Houghton and Munday 1987) to severe or lethal hemorrhage in the gills, liver, kidney, gastrointestinal tract, heart, or brain (Goertner et al. 1994). Goertner et al. (1994) suggested that extreme negative pressures create large enough embolisms to rupture unprotected blood vessels. Bruising and hemorrhages have also been reported in the liver, adipose tissue, and eyes of fish exposed to blasting (Carlson et al. 2011).

Excessive hemorrhaging can result in hematomas (collection of blood outside blood vessels) and hyperemia (an increase in blood flow to tissues) resulting in redness, or erythema. Hyperemia has been observed in the swim bladders, livers (Govoni et al. 2003) and along the base of fins of fish exposed to blasting (Carlson et al. 2011).

Exposed fish can also exhibit hematuria, or blood in the urine, that is observed microscopically as the presence of red blood cells in kidney tubules (Govoni et al. 2003, Godard et al. 2008).

Embolism

Embolisms result from extreme pressure differences in and outside of blood vessels resulting in the formation of gas bubbles that combine into embolisms (Goertner et al. 1994). Embolisms were observed in the eyes, gills, fins, heart, swim bladder, and kidney from exposure to blasting (Carlson et al. 2011). Accumulation of gas can also cause outward displacement of the eyes (Kearns and Boyd 1965, Godard et al. 2008, Carlson et al. 2011).

Visceral damage

Internal damage can result from swim bladder oscillation including organ damage and evisceration. Torn ribs, ruptured body walls, intestines, organs, and peritoneum damage have been observed in extreme circumstances (Kearns and Boyd 1965, Houghton and Munday 1987, Carlson et al. 2011). Stomach eversions and vent prolapse have been reported in some instances of exposure to blasts (Carlson et al. 2011). Govoni et al. (2003) attributed coagulative liver necrosis (gelatinous substance in dead tissues) in the area of the swim bladder and rupture of the pancreas to blast exposure.

Stress Hormones

Changes in stress hormones can result from exposure to blasting and present as behavioral changes. Sverdrup et al. (1994) studied the effects of sub-lethal explosions and found that plasma cortisol declined for about 6 hours followed by a gradual rise about 48 hours after exposure. Secondary stress hormones albumin and sodium were significantly lower at 24 and 48 hours. Elevated levels of plasma cortisol indicate a primary response to stress; in fish this includes bursts of jumping and rapid swimming. Fish exposed to non-lethal underwater blasts may not be able to express the alarm reaction by an intermediate release of primary stress hormones because of temporary endothelial impairment that could prohibit the coeliaco-mesenteric artery from contracting in response to albumin (Sverdrup et al. 1994). Behavioral changes such as the inability to express the alarm reaction may make fish more susceptible to predation. Teleki and Chamberlain (1978) reported heavy gull predation on stunned fish after blasts.

Octavolateral system

Damage to the octavolateralis system can also present as behavioral changes. The octavolateralis system describes mechanosensory function and is composed of the auditory, equilibrium, lateral line, and electrosensory systems. Intense sounds can damage hair cell sensor receptors in the inner ear under specific conditions causing temporary hearing loss or threshold shift (Hastings and Popper 2005). Neuromasts within the lateral line regulate dynamic equilibrium and consist of clusters of cilliary hair cells that detect water movement and displacement (Barton 2007). Cilliary hairs and otoliths in the upper ear regulate static equilibrium and can be temporarily or permanently damaged by rapid changes in pressure (McCauley et al. 2003) causing disruption in orientation and locomotion, predator detection, and navigation. Goertner et al. (1994) observed erratic swimming and bleeding around otoliths in fish exposed to underwater explosions.

Others

Scale loss and abrasion on the body in the area of the swim bladder can result from an expanded or outwardly burst swim bladder (Christian 1973). Carlson et al. (2011) thoroughly documented several blast-induced barotrauma injuries in rainbow trout and Chinook and include a photographic guide in their final report. Godard et al. (2008) discuss fish injury in depth and include a summary of injuries reported in other studies.

4.2 METHODS OF ASSESSING INJURIES AND MORTALITY

Several injury classifications have been applied during post exposure injury assessments. Hubbs and Rechnitzer (1952) used as classification system with 5 degrees of injury, others have used 7 and 3 degrees of injury (Teleki and Chamberlain 1978, Houghton and Munday 1987). Carlson et al. (2011) used a new approach termed the Fish Response Severity Weighted Index (FRSWI) that provides a weighted sum of the number of injury types and severity based on the physiological cost to the fish and how likely injuries are to affect performance and survival.

4.3 EMPIRICAL STUDY RESULTS

Many experiments have been conducted to assess the effects of blasting on fish, however variables in study design, level of detail reported, and overall conclusions complicate comparisons. The following literature summaries are limited to investigations examining the effects and tolerances of blast induced overpressures on salmonids through the use of caged specimens and pressure monitoring. Most caged fish studies utilize young or juvenile salmon due to logistical difficulties obtaining and studying larger adults. Additionally, Yelverton et al. (1975) found that larger fish (within and between species) could withstand higher impulse and peak pressures than smaller fish.

Yelverton et al 1975

The primary goal of Yelverton et al. (1975) was to determine fish tolerance levels and injury/mortality relationships to underwater blast overpressures. Caged fish were exposed to unconfined underwater detonations in an artificial test pond. Thirteen body weights and eight species of fish were oriented in cylindrical cages and exposed at varied depths. Some fish were placed against a steel plate to determine the effect of a reflecting surface. Tourmaline sensors and oscilloscopes measured and recorded blast overpressures at the location of the fish. Fish were necropsied upon death and all remaining fish were necropsied at two weeks.

There was no detectable difference in the response of fish with ducted (physostomous) and non-ducted (physoclistous) swim bladders. Amongst fatally injured fish there was no pattern of sinking or floating and 90 percent of dying fish died within four hours. Results for fish exposed near a steel plate reflecting surface were not significantly different that those without.

The underwater blast impulse levels required for 50 percent mortality, 1 percent mortality, and no-injury were determined for eight species of fish. Investigators found a good correlation between impulse causing 50 percent mortality and body weight of several species of fish. Impulse levels that caused mortality ranged from 1.7 psi•msec for 0.02 g guppy (*Lebistes reticulates*) fry to 49.5 psi•msec for 744 g carp (*Cyprinus carpio*). For rainbow trout (*Salmo gairdneri*) 0 percent mortality occurred at impulses 5 to 15 psi•msec, and no injuries occurred at 5 psi•msec and corresponding peak pressures of 128 psi (882.5 kPa). Rainbow trout experienced 20 to 90 percent mortality at impulses between 19 and 25 psi•msec and peak pressures of 285 psi (1965 kPa).

Yelverton et al. (1975) reported that impulse correlated better with fish injury than peak pressures. Larger fish compared within and between species could withstand higher impulses before mortality. The findings of this study have been widely referenced and its impulse model tested by several researchers with varying results (Gaspin et al. 1975, Hill 1978, Wright 1982, Munday et al. 1986, Keevin and Hempen 1997).

Teleki and Chamberlain 1978

In 1975 the Steel Company of Canada deepened the bottom of Nanticoke Lake Erie. The goals of this study were to examine the effects of blasting on fish in the area and determine relationships between charge type and size to species-specific injuries and mortality. Caged fish were caught in the area and exposed in wire-mesh cages to blast overpressures. More than 200 confined blasts consisting of 50 to 600 lbs (23 to 272 kg) were detonated in bedrock below the lake under 13 to 26 ft (4 to 8 m) of water. Fish were exposed in up to 9 cages between 49 and 492 ft (15 and 150 m) from blasting. After exposure, fish were held for observation and later necropsied. Blast overpressures at the fish cages were measured with hydrophones and calculated in some instances. Monitoring data suggested that the denser the material being blasted the more rapidly the pressure wave decayed. Additional monitoring results are reported in McAnuff and Booren (1989).

Results for all species of fish indicated that pressure exposures between 4.3 and 12.3 psi (30 and 85 kPa) caused 10 to 20 percent mortality and fatal injuries, and 10.0 to 21.8 psi (69 to 150 kPa) caused 95 percent or greater mortality. Results for rainbow trout alone were 10 to 20 percent mortality at 12.3 psi (85 kPa) and 95% mortality at 14.5 psi (100 kPa).

Fernet 1982

This report details the results of a caged fish experiment conducted during pipeline blasting in the Bow River in Alberta, Canada. A total of eight cages with 10 fish each were placed 33 to 146 ft (10 to 45 m) downstream and 33 to 82 ft (10 to 25 m) upstream of the blast. Four pressure transducers were installed on the four upstream fish cages. A bubble curtain was also installed downstream of the blast and determined to be ineffective in flowing water conditions. Caged rainbow trout were exposed to a single trench blast of 3,876 lbs (1,758 kg) detonated beneath 7 ft (2 m) of water.

Seven of the fish caged 33 ft (10 m) downstream died immediately and the remaining three fish died within two hours. All other fish were necropsied and their injuries rated according to damage criteria established by Hubbs (1960). No other mortalities or injuries were noted in the 70 remaining fish. Unfortunately, pressures were not recorded at the cage where fish died. In cages where overpressures were measured, no injury or mortality occurred at 33.0 to 289.5 psi (227.5 to 1996.0 kPa) and corresponding impulses of 72 to 1606 psi•msec.

Bird and Roberson 1984

This draft ADFG report details the results of caged fish experiments performed in conjunction with highway blasting in Keystone Canyon adjacent to the Lowe River near Valdez, AK. The study objective was to determine whether blasting would produce adverse effects on fish in the area. Wild Dolly Varden (*Salvelinus malma*) and coho (*Oncorhynchus kisutch*) fry were trapped onsite and coho and chum (*Oncorynchus keta*) fry and fingerlings were obtained from a local hatchery. Wild fish were held in plastic mesh boxes and hatchery fish were held in plastic jugs filled with salt water. Fish cages were placed between 89 and 295 ft (27 and 90 m) from the blasts. Shots were 85 to 90 ft (26 to 27 m) from the river and charge weight per delay ranged from 102 to 1,673 lbs (46 to 759 kg) for up to 16 delay periods.

Monitoring equipment measured peak overpressures between 0.8 and 2.7 psi (5.5 and 18.6 kPa) and maximum PPVs of 0.8 to 1.7 in/s (20.3 to 43.1 mm/s). No internal or external trauma was discovered during necropsies performed 24 hours post exposure. The ADFG blasting guidelines were partially based on this report (ADFG 1991).

Munday et al 1986

Munday et al. (1986) reported the results of a monitoring program designed to assess the effects of a blasting project on resident fish populations in Vancouver Harbour, British Columbia. Confined charges were detonated in conglomerate rock beneath 33 to 66 ft (10 to 20 m) of water to deepen a ship-loading berth. Caged coho smolts were held in cylindrical plastic mesh cages placed at various distances at the surface and 20 ft (6 m) deep. Piezoelectric hydrophones measured overpressures in fish cages, at ground/sea, mid-water, and sea/air interfaces.

Bubble curtains were used to protect concrete pier cribbing and overpressures were measured on either side of the air curtain. Results indicated a 17 to 73 percent reduced peak pressure and increased impulse possibly due to an increase in the duration of the positive phase of the wave.

Peak overpressure and impulse levels were 6 to 36 percent higher inside cages than out. Fish exposed at 3 ft (1 m) deep suffered 22 percent mortality at impulse levels between 16.1 psi•msec (1.1 bar•msec) and 100 percent mortality at 52.2 psi•msec (3.6 bar•msec). Surface caged fish experienced 50 percent mortality at 43.5 psi•msec (3.0 bar•msec) and fish at 20 ft (6 m) survived much higher impulse levels, one group showed no effect at 59.8 psi•msec (4.12 bar•msec).

Results were compared to a previously established injury prediction model (Yelverton et al. 1975) and lethal levels were determined to be much higher in this study. For instance, Munday et al. (1986) observed 50 percent mortality at 36.3 to 43.5 psi•msec (2.5 to 3.0 bar•msec) compared to a predicted 11.6 psi•msec (0.8 bar•msec) using the model in Yelverton et al. (1975). The authors indicated this could have been a result of many factors including longer duration shock waves from buried charges, higher resistance to shock damage by salmonid species, different methods of calculating impulse, or some difference in physical experimental design such as cages.

Houghton and Munday 1987

A field experiment was designed to measure overpressures and effects on juvenile salmonids and pacific herring resulting from linear explosives similar to those used in seismic surveys. Fifty-four charges of detonating cord in various strengths and lengths were detonated on or just above the bottom of a transition zone area in Resurrection Bay near Seward, AK. Water depths at test sites were up to 24 ft (7.3 m) deep. Bottom substrate was loose shale and rock rubble.

Hydrophones placed inside cylindrical fish cages made of plastic mesh measured overpressures for 21 of 54 total detonations. Hatchery obtained coho and chum salmon, and wild caught herring were held in cages 3 to 30 ft (1 to 9 m) deep in an array 75 to 318 ft (23 to 97 m) extending from charges. Fish were necropsied 24 to 48 hrs post exposure and injuries and mortality were classified into three levels.

Several pressure wave parameters were compared to lethal thresholds including peak pressure, impulse, and energy flux density. Maximum positive pressure was better correlated with 50 percent lethal levels than impulse or energy flux. Coho salmon experienced 50 percent mortality at 19.3 psi (133 kPa, 1.33 bars) and at 2.1 psi•msec (14.7 kPa•msec, 0.147 bar•msec). Similarly, chum salmon experienced 50 percent mortality at 21.0 psi (14.4 kPa, 1.44 bars) and at 1.6 psi•msec (11.4 kPa•msec, 0.114 bar•msec).

Godard et al. 2008

An increase in oil and gas exploration in Canada's Northwest Territories (NWT) prompted an investigation into the effects of seismic blasting near frozen water bodies on fish and a re-evaluation of the DFO guideline levels. In March 2004 caged fish were exposed to seismic charge detonations in the Mackenzie Delta in Inuvik. Rainbow trout eggs, fry, and juveniles were contained in plastic bags held in a nylon mesh cage suspended approximately 6.5 ft below 6.5 ft thick ice and 6.5 ft (2 m) above the lake bottom. Charges were detonated 5 to 20 ft (1.5 to 6 m) away from cages and buried 3 to 10 ft (1 to 3 m) deep in clay substrate with organic overburden. Three hydrophones measured pressures at the fish cage.

Rainbow trout eggs and sac fry were exposed to peak pressures of 0, 9.3, 15.2, 33.1, and 40.6 psi (0, 64, 105, 228, and 280 kPa) and juveniles exposed to 0, 10.0, 34.7, and 40.6 psi (0, 69, 239, and 280 kPa). Specimens were held briefly for observation post exposure and a subset was selected for necropsy and histopathological exam. Eggs held in-water experienced no significant impacts at any exposure level. Sac fry examined for swim bladder tears were not significantly different than the control group.

Juvenile rainbow trout were thoroughly examined for injuries and tissue samples were processed for histopathology. Eye distension was significant among fish exposed to 10.0 and 40.6 psi (69 and 280kPa), but not the 34.7 psi (239 kPa) exposure group. The histopathology exam revealed multiple hemorrhages and hematuria (blood in urine) in exposed fish. There was no significant difference in thrombocyte (promotes blood clotting) totals in the livers, or in any of the gill parameters examined between exposed and control fish.

Results suggested that the onset of injury in rainbow trout exposed to seismic charge detonation under surface frozen bodies of water begins around 10.0 psi (69 kPa). These findings indicated that pressures below DFO guidelines levels (14.5 psi, 100 kPa) could harm fish. Subsequently, the DFO Western Arctic Area recommends that maximum peak pressures not exceed 7.3 psi (50 kPa).

Carlson et al 2011

During the winter of 2009/2010 blasting was conducted to deepen a stretch of the Columbia River near Saint Helens, OR. The report by Carlson et al. (2011) details the methods and results of compliance monitoring and a required caged fish study. Ninety-nine confined blasts with a maximum charge weight of 90 lbs (41 kg) per delay were shot in basalt beneath approximately 40 to 60 ft (12 to 18 m) of water over the duration of the project. Compliance monitoring included a marine mammal and protected birds watch program, a sturgeon monitoring program, survey and estimation of take for Endangered Species Act listed fish and a caged juvenile salmonid study. Only the caged fish study results are discussed here.

Hatchery obtained juvenile Chinook salmon and rainbow trout were caged and placed (33 to 127 m) from blasts. Wedge shaped cages were designed to provide flow relief with a front solid baffle and screen mesh on the sides. Cages were deployed onto an anchored barge outfitted with pressure transducers and data acquisition systems to record blast pressures. Test fish were either necropsied immediately, at 24, or 48 hours post-blast. Control fish were deployed similarly to test fish and necropsied to document damage incurred from deployment procedures. Fish were examined for pre-existing conditions, barotrauma, and physical trauma. Internal and external injuries were categorized and rated for severity based on a Fish Response Severity Weighted Index (FRSWI).

A total of 1,118 fish were examined post exposure. No significant difference was found between the injuries sustained between rainbow trout and Chinook salmon. As maximum positive pressure increased, so did the number of injuries per fish. Observed absolute blast pressures ranged from 4.8 to 84.0 psi (33 to 576 kPa). Out of 24 measures of blast strength regressed against FRWSI for both species, blast maximum positive pressure (BMPP) provided the most significant correlation. A common model provided describes the relationship between FRSWI and BMPP. The report concludes that this model be used in future assessments of blast effects on depth-acclimated juvenile salmonids from buried explosive charges.

The BMPP level that juvenile salmonids began to experience injury or mortality is not identified; however, figures in the report indicate that the number of fish with three or more injuries increases with pressure and a notable increase is visible around 14.5 psi (100 kPa). A second paper describing the overpressure monitoring equipment (Martinez et al. 2011) makes reference to the findings in (Carlson et al. 2011) while describing a case study. Martinez et al. (2011) state, "at lower BMPPs such as 2.1 to 4.8 psi (14.5 to 32.8 kPa), 0 to 2 injuries per fish were common and at higher BMPPs, such as 14.9 to 23.6 psi (103.0 to 163.0 kPa), 3 to 8 injuries per fish were observed. The severity or physiological cost associated with each injury type significantly increased with blast maximum positive pressure as well. For example, mild injuries, such as enlarged capillary beds and hematomas, comprised more of the total injuries per fish recorded at lower blast pressures than at higher blast pressures. Conversely, severe injuries, such as hemorrhaging livers and swim bladders, comprised more of the total injuries per fish recorded at higher blast pressures than at lower blast pressures." While this information is not clearly stated in the original report, further analysis and findings of the Columbia River project data are in progress (C. Woodley, Senior Scientist, Pacific Northwest National Laboratory, WA, personal communication).

5.0 CONCLUSIONS

The results of studies that examined the effects of mechanical or blast induced transient impulse vibrations on salmonid embryos are summarized in Figure 4. Numerical values represent reported PPVs and the species of embryo exposed. No mortalities were observed in embryos exposed to 1.1 in/s (28 mm/s, Faulkner et al. 2006) and 5.2 in/s (132 mm/s, Faulkner et al. 2008). The lowest reported exposure level resulting in embryo mortality was 5.8 in/s, (147 mm/s) as reported by Jensen (2003) for Chinook salmon eggs subject to mechanical impact. For comparison, the ADFG and Canadian DFO recommended maximum blast induced velocity in spawning beds is 0.5 in/s (13 mm/s).

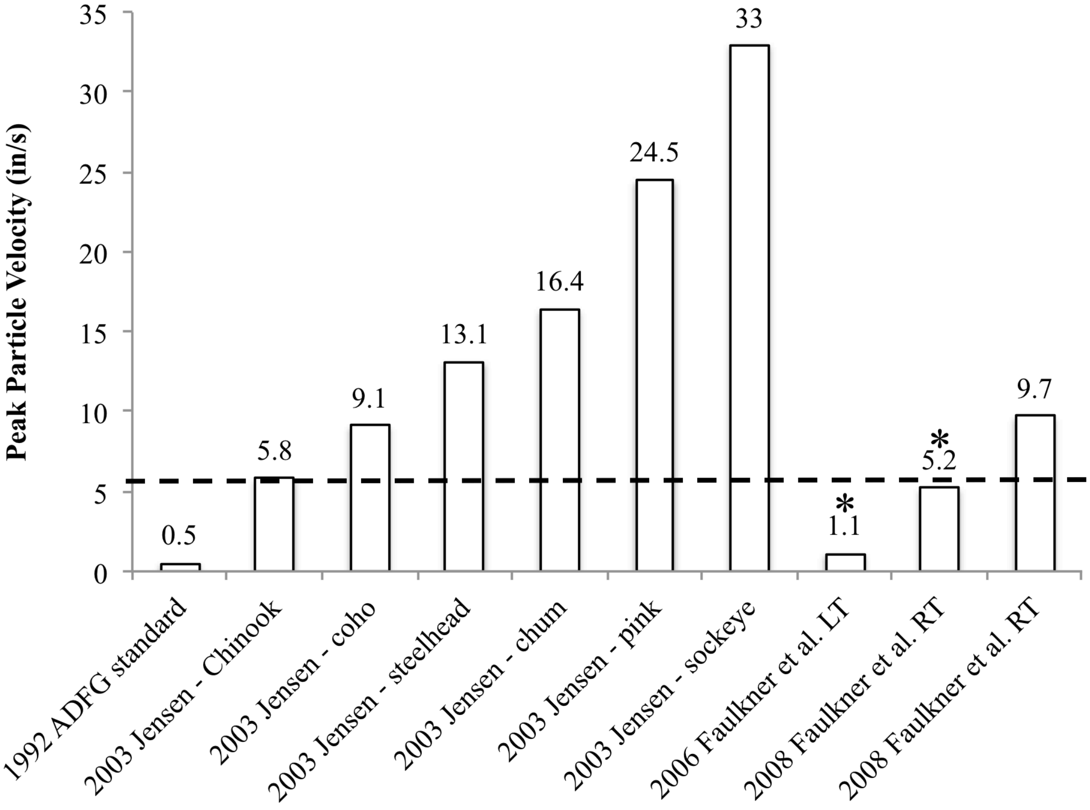

Figure 4. Reported PPV exposures for all studies reviewed. Dashed line (5.8 in/s) indicates the lowest measured PPV that caused mortality (Jensen 2003). Values with asterisk (*) indicate reported exposures that did not cause mortality. LT = lake trout, RT = rainbow trout.

Peak overpressure exposure levels reported in the caged fish studies reviewed are shown in Figure 5. The results summarized are for juvenile salmonids only. As previously stated, logistical complications make caging adult salmon difficult and previous results have shown that larger fish are less sensitive to blast induced overpressures (Yelverton et al. 1975). Yelverton et al. (1975) and Fernet (1982) reported no injury or mortality for fish exposed to 128 and 290 psi (883 and 1999 kPa) respectively. The lowest peak pressure to cause injury was 10.0 psi (69 kPa) reported by Godard et al. (2008). The ADFG (1991) recommended maximum blast induced overpressure of 2.7 psi (19 kPa) was based on Bird and Roberson's (1984) results.

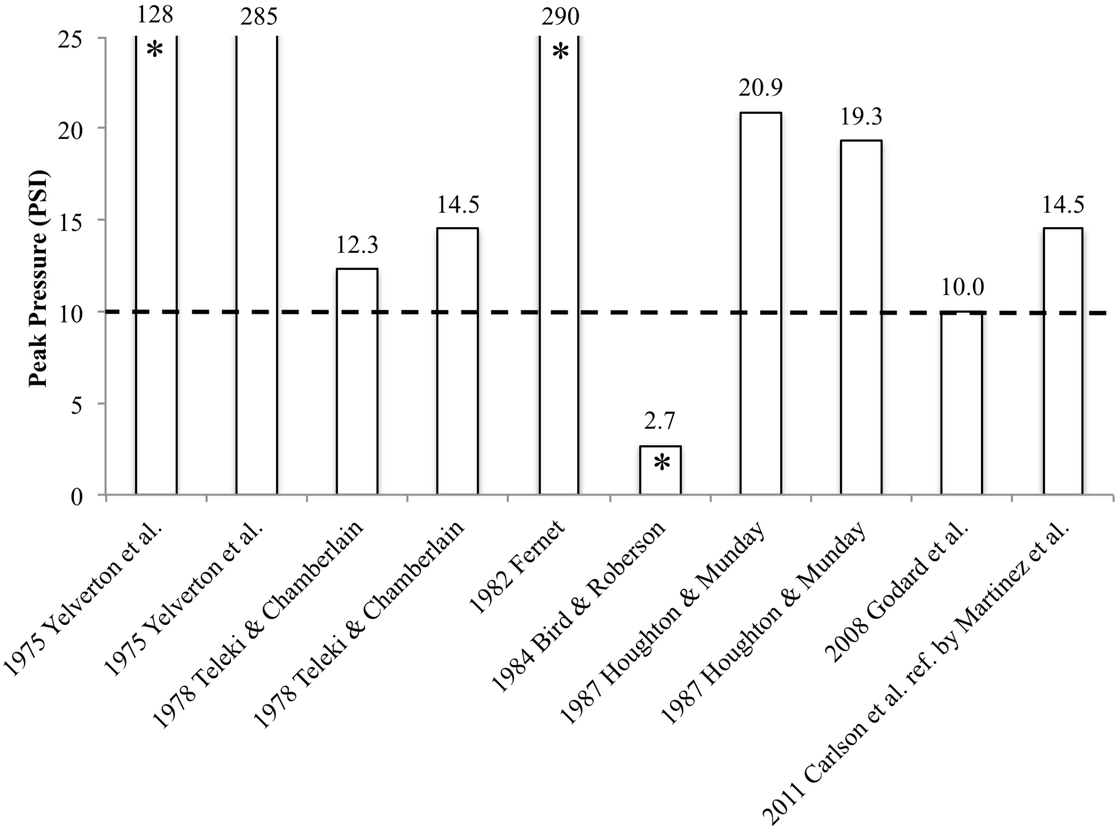

Figure 5. Reported blast peak overpressures for all caged fish studies. Dashed line (10.0 psi) indicates the lowest reported salmonid injury reported (Godard et al. 2008). Asterisk (*) represents reported peak overpressures where no injuries or mortalities were observed.

6.0 DISCUSSION

The current ADFG blasting guidelines (ADFG 1991) limit blast induced overpressure to 2.7 psi (19 kPa) when fish are present, and velocities to 0.05 in/s (13.0 mm/s) in spawning beds. The results of literature reviewed in this report indicated that ADFG levels are more than sufficient to protect fish and embryos that may be present during blasting. It is unclear which parameter of blast strength is the best predictor of fish injury or mortality and threshold levels are not exact. Results of several studies indicate that the most sensitive species of salmonid embryos begin to experience mortality around 5.8 in/s (147 mm/s) and that juvenile salmonids are susceptible to injuries from blast induced overpressures as low as 10.0 psi (69 kPa). If a cautionary approach is applied, velocity and overpressure limits for blasting near salmonids could be raised to levels below those shown to cause injury or mortality as determined by ADFG resource managers. In order to better define the onset levels of injury and mortality, mechanical shock and caged fish experiments should be carefully designed and performed by qualified individuals.

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8.0 GLOSSARY

Attenuation	the reduction in strength of a pressure or vibration over distance
Barotrauma	physical damage to body tissues caused by extreme changes in pressure
Blasting	the firing of explosive materials for such purposes as breaking rock or other material, moving material, or generating seismic waves.
Delay	a distinct pause of predetermined time between detonation or initiation impulses, to permit the firing of explosive charges separately
Detonating cord	a flexible cord containing a center core of high explosive that may be used to initiate other high explosives
Energy flux	the rate of energy transport across a unit area
Epiboly	also called gastrulation; an early embryonic developmental stage where the embryo spreads over the yolk mass
Explosion	a chemical reaction involving an extremely rapid expansion of gases usually associated with the liberation of heat
Fragmentation	the breaking of a solid mass into pieces by blasting
Frequency	the number of complete cycles of a periodic process occurring per unit time, reported in Hertz (Hz)
Geophone	an instrument used to detect and measure ground vibration
Histopathology	microscopic examination of tissues
Hydrophone	an instrument used to detect and measure underwater sound
Impulse	the time-integral of a pressure signal
Overburden	material of any nature lying on top of a deposit of material
Overpressure	the change in pressure from ambient pressure
Physoclistous	‘closed swim bladder,’ no connection to the digestive tract
Physostomous	‘open swim bladder,’ pneumatic duct connects the swim bladder to the alimentary canal allowing bladder to be filled or emptied via the mouth

Rarefaction	negative pressure
Scaled distance	A factor relating similar blast effects from various weight charges of explosive material at various distances. Scaled distances are obtained by dividing the distance a fractional power of the weight of the explosive materials.
Seismograph	an instrument used in monitoring blasting operations to record ground vibration, air and water overpressures
Shock wave	a transient pressure pulse that propagates at supersonic velocity