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# Assessment and Mitigation of Marine Explosives: Guidance for Protected Species in the Southeast U.S.

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## 1. Purpose

This document is intended to provide recommendations for assessing impacts to protected species (threatened and endangered species and marine mammals), and mitigation planning for the use of explosives during the construction, operation, maintenance, or decommissioning phases of a project. These recommendations may assist in the preparation of biological assessments for purposes of section 7 consultation under the Endangered Species Act (ESA) or for preparation of incidental harassment applications under the Marine Mammal Protection Act (MMPA). Discussion of the physics of explosions is limited to explanatory information, and good summaries are available elsewhere (Department of the Navy 1998 and 2001, Keevin and Hempen 1997).

Killing, injuring, or harassing threatened and endangered species and destruction or adverse modification of critical habitat is prohibited under the ESA. Section 7 of the ESA (16 U.S.C. § 1536(a)(2)) requires Federal agencies to consult with the Secretary of Commerce, through NOAA, to insure that "any action authorized, funded, or carried out by such agency is not likely to jeopardize the continued existence of any endangered species or threatened species or adversely modify or destroy [designated] critical habitat" (see also 50 C.F.R. part 402). Similar protections from injury and harassment apply to all marine mammals under the MMPA. In the event that a project will result in a "take" the federal action agency or the project applicant would be required to obtain an incidental take authorization in advance from NMFS (16 U.S.C. §§ 1371(a)(5)(A) and (a)(5)(D)).

The following sections summarize the potential effects from explosives on protected species of vertebrates (sea turtles, fishes, and marine mammals) found in the southeast United States that are managed by the National Marine Fisheries Service (NMFS), discuss criteria to assess potential impacts, and recommend measures to minimize impacts to those species. Specific criteria to estimate ranges of effects on marine mammals and sea turtles have been developed, and this document will be updated when NMFS exposure criteria are revised. Although no specific criteria have been developed for listed species of fishes, some recommended approaches to estimate the range of impacts are discussed for ESA-listed species in southeast U.S. waters. Information on endangered and threatened species listed and critical habitat designated in NMFS' Southeast Region are available at http://sero.nmfs.noaa.gov/pr/pr.htm.

## 2. Overview of Impacts to Protected Species

Underwater explosions may affect marine life by causing death, injury, temporary threshold shifts (TTS or recoverable hearing loss), or behavioral reactions, depending on the distance an animal is located from a blast. An underwater explosion is composed of an initial shock wave, followed by a succession of oscillating bubble pulses. A shock wave is a compression wave that expands radially out from the detonation point of an explosion. At a distance from a detonation, the propagation of the shock wave may be affected by several components including the direct shock wave, the surface-reflected wave, the bottom-reflected wave, and the bottom-transmitted wave. The direct shock wave results in the peak shock pressure (compression) and the reflected wave at the air-water surface produces negative pressure (expansion). For an explosion with the same energy and at the same distance, an underwater blast is much more dangerous to animals

than an air blast. The shock wave in air dissipates more rapidly and tends to be reflected at the body surface; in water the blast wave travels through the body and may cause internal injury to gas-filled organs due to impedance differences at the gas-liquid interface.

Beyond the distance from a detonation causing injury, explosives use in designated critical habitat, during certain times of year, or occurring in other biologically important habitats (e.g., migration corridors, spawning and nesting areas, and juvenile habitats) could have potentially adverse consequences on animals. In response to noise, behavioral reactions could potentially result in impairment of feeding, sheltering, reproduction, or other biologically important functions of animals. Exposure to a noise can also result in temporary or permanent hearing impairment, depending on the sound pressure level and exposure duration. Therefore, the hearing abilities of animals and behavioral disturbance are important considerations when assessing the potential impacts from projects resulting in noise.

### 2.1. Effects on Sea Turtles

Explosions are known to injure and kill sea turtles (Duronslet et al. 1986, Gitschlag 1990, Gitschlag and Herczeg 1994, Klima et al. 1988, O'Keefe and Young 1984). NMFS studied the effects of offshore oil and gas structure removals using 23 kg (50 lb) of nitromethane (Klima et al. 1988). Loggerhead (*Caretta caretta*) and Kemp's ridley (*Lepidochelys kempii)* sea turtles were located at distances of 213.4 m (700 ft), 365.8 m (1,200 ft), 548.6 m (1,800 ft), and 914.4 m (3,000 ft) from the platform removed with explosives. The charges were placed inside platform pilings at a depth of 5 m below the mudline. Four sea turtles within 365.8 m of the detonation were unconscious, as well as an individual at 914.4 m (3,000 ft). Sea turtles were expected to have drowned if not recovered from the water following the detonation. All turtles exposed to the blast exhibited everted cloacas and vasodilation lasting 2-3 weeks.

The sea turtle ear appears to be adapted to both aerial and aquatic environments. Sea turtles have a primitive reptilian ear and are considered to be hearing generalists, having limited hearing abilities at lower frequencies. Although there is some variation in sea turtle hearing measurements between species and size classes (Ketten and Bartol 2006), the available data suggest that species of sea turtles are likely sensitive to frequencies from approximately 100 Hertz (Hz) to 2,000 Hz (Lenhardt 1994, Lenhardt et al. 1996, McCauley et al. 2000a and 2000b, Moein et al. 1994, O'Hara and Wilcox 1990), with greatest underwater hearing sensitivities below 1,000 Hz (Ketten and Bartol 2006). Behavioral reactions to the sound produced from explosions may be important if they occur in biologically important areas such as foraging areas, near nesting beaches during nesting season, or in developmental juvenile habitats.

### 2.2. Effects on Fishes

Fishes with air bladders are generally more susceptible to mortality and injury from explosions than sea turtles and marine mammals due to the inability to effectively observe them from the surface, their relatively more abundant numbers, and physiological differences. Fishes with swim bladders are more likely to be killed or injured than fishes without swim bladders. The primary cause of fish mortality from explosions usually results from tissue damage to gas filled organs such as the intestinal tract and swim bladders. Internal injuries to other organ systems have resulted from the rapid expansion of the swim bladder as a result of exposure to negative pressures or "cavitation hat" from a shock wave. The magnitude of damage has been correlated

with the mass of individuals, such that smaller size classes would be expected to incur greater blast injury than larger size classes at the same exposure level (Yelverton et al. 1975, Goertner 1978, Wiley et al. 1981, O'Keefe 1984, and Munday et al. 1986, Moser 1999).

Threatened and endangered fish species in NMFS' Southeast Region include shortnose sturgeon (*Acipenser brevirostrum*), Gulf sturgeon (*Acipenser oxyrinchus desotoi*), and the smalltooth sawfish (*Pristis pectinata*). The available information suggests species of sturgeon would be much more vulnerable to blast injury than smalltooth sawfish. Shortnose sturgeon and Gulf sturgeon have physostomus (ducted) swim bladders; the smalltooth sawfish lacks a swim bladder altogether. Fishes without swim bladders appear to be extremely resistant to blast injury; however, species with swim bladders, such as species of sturgeon, are expected to be more vulnerable to shock waves. Some studies have reported that sturgeon exhibit less severe blast damage than other species tested (Moser 1999a and 1999b). These results were attributed to the larger size of sturgeon used in the studies; however, sturgeon have been reported to be killed by underwater explosions (Keevin et al. 2002). Although smalltooth sawfish lack a swim bladder, injury and mortality in this species may be associated with blast trauma to other organs within very close proximity to a blast. In other species of fishes without swim bladders, gill hemorrhaging, and brain hemorrhaging due to differential motion of the otoliths has been reported (Goertner et al. 1994), with blood loss from hemorrhaging gills primarily causing death.

In marine species, the lateral line and ear are the primary modes of sound reception. The lateral line responds to differences in motion of the fish in the immediate environment (two to three body lengths from the fish) and is sensitive to low frequencies (<1 to 345 Hz). The ear detects signals at considerable distances from the fish over a much wider range of frequencies, from well below 50 Hz to over 2,000 Hz (Schwartz 1985, Popper and Carlson 1998). In some species the swim bladder is connected to the inner ear, or air bubbles associated with the inner ear are present that function as an important auditory receptor for higher frequency sounds. Studies show that sturgeon have restricted hearing ability between approximately 100 and 2,000 Hz, with best hearing at frequencies between 100 and 400 Hz (Fay and Popper 2000, Lovell et al. 2005, Meyer and Popper 2002, Meyer et al. 2003, Popper 2005). Smalltooth sawfish and other fishes lacking swim bladders are hearing generalists (see Casper et al. 2003), likely having best hearing at frequencies below 1,000 Hz.

### 2.3. Effects on Marine Mammals

Blast damage in marine mammals has been investigated using both submerged terrestrial mammals (Goertner 1982, Yelverton et al. 1973, Richmond et. al 1973) and cadavers (Myrick et al. 1990, Ketten et. al 2003). At close ranges to a detonation, mortality and life threatening injuries may occur. At increasing distance from the blast, the effects of the shock wave lessen, but effects such as hearing loss and behavioral responses may still occur. There are a variety of factors that may affect noise effects on marine mammals. Marine mammals are at greatest risk of injury when they are at the same depth as, or slightly above, the explosion (Keevin and Hempen 1997). Risks drop off quite sharply above and below this depth; however, the pressure waves produced from an explosion may propagate very differently, depending on environmental factors. Additionally, smaller marine mammals are more susceptible to blast injury than larger animals at the same exposure levels. Frequently occurring or repeated detonations over a given

time period may cause behavioral changes that disrupt biologically important behaviors or result in TTS.

The hearing abilities of marine mammals are generally classified as lower-frequency hearing for mysticetes (baleen whales) and higher-frequency hearing for odontocetes (toothed whales). Based on anatomical studies, mysticetes are believed to generally hear sounds in the 0.01 to 20 kHz range, depending on the species (e.g., Helweg et al. 2000, Parks et al. 2001, 2007). Odontocetes generally hear over a much broader range of higher frequencies from approximately 0.2 to 180 kHz (e.g., Cook et al. 2006, Erbe 2002, Houser and Finneran 2006, Kastelein et al 2003, Szymanski et al. 1999) with best hearing between approximately 5 and 100 kHz, depending on the species. Increasingly, more hearing measurements are becoming available for more odonotcete species and have been summarized elsewhere (Nedwell et al. 2004); however, the general range of hearing abilities described above can be used for planning projects that result in infrequent, impulsive sounds from underwater detonations of explosives.

**2.4. Behavioral Reactions to Detonations**

At ranges beyond those causing injury, animals are susceptible to behavioral disturbances from underwater noise in the frequencies of their hearing range. Explosions produce loud, broadband noise that is audible to many species, but the main frequencies produced are often influenced by the medium being blasted (e.g., rock, concrete, and pilings) and blasting technique (e.g., placement inside or outside the structure, burial or borehole depth, and type of charge). Important behavioral effects on feeding, resting, and reproduction should always be considered during project planning.

Based on the duration of noise produced from construction activities, repeated exposure to acoustic energy (e.g., pile driving, geophysical surveys, dredging, and vessel noise) could potentially result in a broader range of behavioral effects than single, impulsive energy waves, such as those resulting from detonations. Detonations resulting in a single, instantaneous detonation would not be expected to result in significant behavioral disturbance; however, temporary reactions or startle responses to the noise may occur. Likely reactions to a single detonation may range from no reaction (Madsen and Møhl 2000), annoyance, attraction to or avoidance of the noise, or a startle response from the sudden onset of the noise (SRS Technologies 2001). Observed reactions could include diving, surfacing, schooling, increased respiration, or swimming away from the noise (Collins et al. 2001, Richardson et al. 2001, Nowacek et al. 2007). The effects of startle responses are usually temporary and minor, although sudden onset of impulsive noises may have potentially adverse consequences (Jehl and Cooper 1980, SRS Technologies 2001).

Recommended exposure levels in which behavioral reactions are expected appear in Table 1. Single, discrete detonation events are generally not expected to result in significant changes in behavior under most circumstances; however, certain life history stages or behavioral states need consideration when assessing impacts of noise. In the southeast U.S., project areas in or near known spawning grounds, calving areas, nesting beaches, important foraging areas, migration corridors, or designated critical habitat may be more likely to disturb animals. These areas may have seasonal or environmental characteristics that are important to protected species. NMFS is available to assist with identifying any areas of potential concern near a project area.

**Table 1.** Onset of behavioral responses to a single impulsive noise.

| Impact Zone | Cetaceans[a] | Sea Turtles[b] | Fishes [c] |
|---|---|---|---|
| Harassment (Behavior) | ≥ 160 $dB_{rms}$ re 1 μPa | $166_{rms}$ dB re 1 μPa or 155 dB re 1 μPa-s | $160_{peak}$ dB re 1 μPa |

[a]Recommended interim criteria for marine mammals
[b]Based on McCauley et al 2000a
[c]Recommended level based on data from Skalski et al. 1992.

Although most single detonations typically don't result in significant behavioral changes, the level of behavioral response of an animal can be strongly dependent on the repetitiveness of the disturbing stimulus. As a guiding principal, projects involving multiple detonations per day should be evaluated for their potential to significantly affect the behavior of an animal. For any projects in which repetitive explosions may occur, the potential for adverse behavioral effects must be evaluated on a project-by-project basis with NMFS.

**3. Defining Zones of Influence**

Defining zones of influence allows NMFS and project planners to estimate the potential area affected and determine appropriate mitigation measures for protected species.

1. **Mortality Zone:** The distance from a detonation within which mortality may occur.

2. **Injury Zone:** the distance from a detonation within which non-lethal injury may occur, but mortality is not expected.

3. **Danger Zone:** The distance from a detonation within which both injury and mortality may occur.

4. **Harassment Zone (TTS):** the distance from a detonation within which temporary hearing loss may occur.

5. **Harassment Zone (Behavior):** the distance from a detonation within which behavioral reactions may occur.

6. **Watch Zone:** an additional buffer zone that may be monitored to detect animals that are heading towards the impacted area. The watch zone radius may vary depending on the type of project and species potentially occurring in the project area.

Different zones of influence should be considered when determining the range of effects from any given noise. Useful terms to describe zones of influence and estimate probable impacts from explosions (and avoidance of) are 1) a mortality zone, 2) an injury zone, 3) a danger zone (mortality and injury zones combined), 4) a harassment zone (TTS), 5) a harassment zone (behavior), and 6) a watch zone (Figure 1). Defining zones of influence is also important to establish common terminology to discuss potential impacts to protected species. The term *impact zone* may also be used in reference to the distance from an explosion within which the

potential for adverse effects may occur, including the potential for mortality, injury, and harassment.

## 4. Calculating Zones of Influence

NMFS' Southeast Region currently accepts three general methods to calculate zones of influence, depending on the activity type: 1) energy and pressure thresholds; 2) unconfined blasts; and 3) confined blasts using stemmed charges. The zones of influence needed for a project area and how they are estimated will vary depending on the method used, as well as project-specific details.

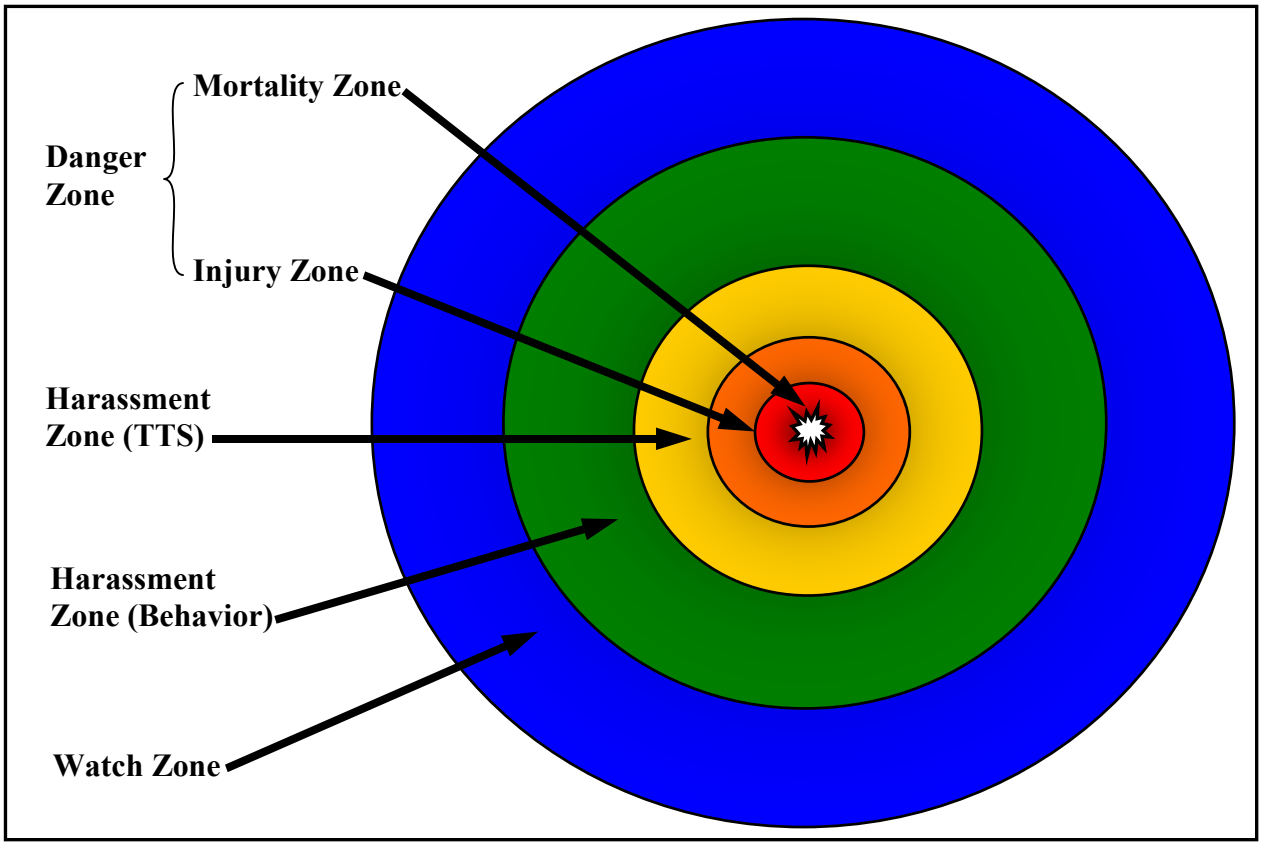


**Figure 1.** An example of zones of influence from explosives detonated in open water.

### 4.1. Energy and Pressure Thresholds

Threshold criteria for marine mammals and sea turtles were initially established for ship shock trials of the SEAWOLF submarine and the WINSTON S. CHURCHILL vessel, and description and derivation of these criteria can be found in the environmental impact statements prepared for these activities (Department of the Navy 1998 and 2001). Recently, these criteria have been revised and are currently undergoing further review by NMFS and may be applied to other protected vertebrate species. Standard impulsive and acoustic metrics used in this document are defined below.

*Peak Pressure*: peak pressure is commonly used to measure maximum positive pressure or peak amplitude of impulsive sources with units of psi.

*Positive Impulse*: Positive impulse is the time-averaged pressure disturbance from an explosive source with units in psi-ms.

*Sound Exposure Level (SEL)*: SEL is the time cumulative sum of squares pressure divided by the duration of the sound. SEL levels have units of dB re 1 $\mu Pa^2 \bullet s$ and other an assessment of risk to multiple exposures, such as pile driving.

*Energy flux density (EFD)*: EFD is the time integral of the squared pressure divided by the impedance. EFD levels have units of dB re 1 $\mu Pa^2 \bullet s$.

*1/3-Octave band*: The 1/3 octave selected is the hearing range at which the subject animals' hearing is believed to be most sensitive.

It is noteworthy that the EFD and SEL metrics are converted to decibels in a slightly different way, but are very similar. The SEL and EFD metrics often are used to refer to the same quantity, namely, the time integral of square pressure divided by the product of sound speed and density. This definition for EFD, however, is not strictly correct for complex pressure fields; SEL may be a more appropriate metric in an analysis of potential impacts from explosive sources. However, both SEL and EFD are reported in the literature and are comparable metrics. NMFS recommends that SEL should be used whenever possible.

*Marine Mammal and Sea Turtle Mortality Thresholds*

To determine the potential physical injury from explosions, pressure thresholds are used based on the mass of the animal. Studies with animals have shown that as the mass of the animal increases, the pressure required to result in lung injury increases. Pressure is commonly measured as positive impulse or peak pressures. Threshold levels can be established to estimate distances from an explosion in which different impacts varying in severity may occur, that may characterize levels at which harassment, injury, or death may be expected. Although body mass is associated with blast injury, there is no not association with auditory and behavioral effects discussed below. Predictive equations for lung injury Equation 1 and example thresholds based on body mass of sea turtles and marine mammals appear in Table 2.

The recommended threshold level for the onset of mortality in sea turtles and marine mammals from explosions (Yelverton and Richmond 1981) is given by:

1% mortality can be estimated by: $LN\ I = 2.588 + 0.386\ Ln\ M$, and

50% mortality can be estimated by $LN\ I = 3.019 + 0.386\ Ln\ M$

where I is positive impulse (psi-ms) and M is body mass (kg).

*Example 4.1*

Using the above equation to find the threshold level at which the onset of mortality (1%) is

expected for a 27 lb (10 kg) juvenile green sea turtle in the Laguna Madre, Texas, we find:

10 kg green sea turtle
LN I = 2.588 + 0.386 Ln (10)
LN I = 2.588 + 0.889
LN I = 3.477

Finding the inverse natural log to solve for impulse (I) yields:
$I = e^{3.477}$
$I = 2.71828^{4.33}$
I = 32.36 psi-ms

In general, smaller animals and their associated smaller impulse values result in larger impact zones. This equation does not consider the possible effects of animal depth; however, it is generally applicable to general estimating the onset of mortality for blasting projects in coastal areas, and it is highly conservative since it estimates the injury range at which only 1% of animals would be expected to experience lung injury. Following the calculation of the appropriate threshold level, the shock wave needs to be modeled to determine the range from the detonation at which the threshold level will be realized. These calculations are complex and require knowledge of the project details, environment, shock wave theory and modeling. These calculations are discussed in greater detail in Department of Defense (2001 and 2007).

To predict auditory effects from single explosions, two different acoustic energy thresholds (dual criteria) may be used to predict effects to sea turtles and marine mammals: a sound exposure level (SEL) and a pressure threshold (Table 2). The auditory criteria resulting in permanent

**Table 2.** Zones of influence for marine mammals and sea turtles from explosions.

| Impact Zone | Criterion Definition | Threshold Level |
|---|---|---|
| Mortality Zone | Onset of severe lung injury (1% of animals; dependent on body mass) | Ln I = 2.588 + 0.386 Ln M[a] |
| Injury Zone | Onset of PTS | ≥46 psi, 230 $_{peak}$ dB re 1 μPa, or 198 dB re 1 μPa$^2$-s |
| Harassment Zone (TTS) | Onset of TTS | ≥23 psi[b], 224$_{peak}$ dB re 1 μPa[c]; or 183 dB μPa$^2$-s at frequencies in any 1/3 octave band above 100 Hz for odontocetes and sea turtles; or above 10 Hz for mysticetes. |

[a]Yelverton and Richmond 1981
[b]Finneran et al 2002
[c]Southall et al. 2007

threshold shift (PTS or non-recoverable hearing loss) and TTS are applicable to single detonation events that do not result in repeated exposures to noise. Since auditory effects have not been

shown to be associated with the size of the animal, specific threshold levels can be used.

However, repeated exposures to noise resulting from consecutive detonations of explosions may result in different threshold levels, this does not typically occur and is limited to some types of military testing and training exercises and special blasting requirements of some construction projects. Longer durations to noise exposure may result in greater magnitude effects on animals, and may require additional consideration when conducting a risk assessment. In general, longer duration noises have a greater likelihood to result in hearing loss, than shorter, impulsive noises of the same intensity.

Some specific models have been developed for some activities using these criteria (e.g., explosive removal of offshore oil and gas structures in the Gulf of Mexico) and are discussed elsewhere (Dzwilewski and Fenton 2003). When deciding which criteria to use, each threshold level must be calculated to determine the more conservative criteria that yields the larger zone of influence. NMFS currently recommends that the SEL be estimated to account for the total energy produced during detonations; however, peak pressure is also acceptable. In cases where empirical data exist, dual criteria exist for the impact threshold. If SEL levels are not used, the equivalent dB unit of measurement used should always be clearly reported.

*Sturgeon and Smalltooth Sawfish Exposure Thresholds*
Blast criteria have yet to be developed for ESA-listed species of fish, and thresholds may vary considerably depending on a number of variables. Smalltooth sawfish lack a swim bladder and would be injured or killed at only short distances from an explosion. Sturgeon would be more vulnerable at greater distances from an explosion. Mortality zones vary greatly based on the mass of the fish, location in water column, and the depth of the charge (Hill 1978, Goertner et al. 1994, Keevin and Hempen 1997, Young 1991, and Yelverton 1975) such that specific criteria are difficult to establish that apply to all blasting scenarios and all size classes of fish. Therefore, calculating zones of influence based on the smallest weight of fish in the project area may be a good predictor of the onset of impacts to fish species in the project area.

A threshold level of 40 psi has been suggested as a conservative range to estimate mortality in fishes (Hempen et al. 2007, Hubbs and Rechnitzer 1952, Keevin 1995, U.S. Army Corps of Engineers 2004), and an open-water blast equation based on this threshold has been proposed (Hempen et. al 2005). The 40 psi criterion is an estimate of 50% mortality, rather than an estimate of the onset of mortality (i.e., 1% mortality) or thresholds at which no mortality is observed. Although this criteria is generally conservative for many non-listed species under the ESA, NMFS believes the 40 psi threshold level is too low to avoid mortality or serious injury for small size classes of listed fish species, especially juveniles, eggs, fry, or pups that are vulnerable at much lower thresholds of injury than adults, but may indeed overestimate ranges for larger individuals. Any mitigation to avoid mortality should consider the a reduction in risk to less than 1% mortality in order to avoid take; otherwise, take may be expected.

Consideration of the life history stage and mass of fishes in the project area, especially very small size classes, should always be considered when determining an appropriate impact zone for listed species. For example, Yelverton et al. (1975) measured the impulse pressures (psi-ms) resulting in 1%, 50%, and 99% mortality in small (avg = 0.25 lb) and large (avg = 1.64 lb) carp.

The results of this study showed 1%, 50%, and 99% mortality at 14.9 psi-ms, 26.2 psi-ms, and 46.2 psi-ms; and 35.1 psi-ms, 49.5 psi-ms, and 69.7 psi-ms for small and large fishes, respectively. Notably, other species of fish measured representing smaller size classes showed an onset of mortality at pressures much lower than those above, with an $LD_{50}$ as low as 1.7 psi-ms for a 0.02-g guppy fry (Figure 2). Although there was some variation in the mortality values, the study found no statistically significant differences between types of swim bladders, and mortality of fishes was significantly correlated with the body weight of fishes across all species (Figure 2).

Using the predicted mortality curve provided by Yelverton et al. (1975), Hastings and Popper (2005) converted the pressure values in Figure 2 to exposure in terms of SEL (Figure 3, from Figure 8 of Hastings and Popper 2005). In Figure 3, the lower regression line suggests that the "no injury" level for the very smallest fish (0.01 g) occurs at 193 dB EFD. Note that there is an estimated range of approximately 7 dB EFD (193-200 dB EFD) for fish masses between 0.01 g and 1,000 g. Impulsive sound with SEL below 193 dB EFD has not been found to injure fishes (Hastings and Popper 2005) and is a good SEL threshold criteria to use when there are various size classes or uncertainty regarding the size of individuals in a project area.

*Summary of Threshold Criteria*

These criteria may be used to establish impact zone areas in which probable impacts can be expected, and appropriate mitigation measures designed to avoid or minimize the risk of harm to protected species. A discussion of the calculations conducted for these criteria are provided in the environmental impact statement prepared for the shock trial of the *Mesa Verde* (Department of Defense 2008). NMFS regards these criteria (Table 3) as the preferred approach to estimating impacts on sea turtles and marine mammals; however, potential impacts to sturgeon and the smalltooth sawfish are more difficult to quantify by discrete threshold levels and is dependent on the size class and/or life history stage of fishes in the project area. Additionally, many project planners often do not have the necessary information on the project to model the required distance at which the thresholds are realized. In absence of all the information necessary to complete the calculations, reasonable assumptions may be necessary to model shock wave propagation and determine dual criteria thresholds for protected species.

With information on the noise characteristics of the detonation and species affected, accurate estimates of impact zones can be determined for sea turtles and marine mammals. Some limitations of the criteria include assumptions about the propagation of shock waves, depth of charge, and variations in propagation environments at different project areas. Although specific threshold criteria can be set for protected species, modeling of threshold levels from explosions may be limited by modeling capabilities, and conservative assumptions regarding impact zones and potential effects to species may be needed. Because there are many other variables to consider, NMFS may request field verification measurements to be made prior to establishing final zones of influence when a large degree of uncertainty exists.

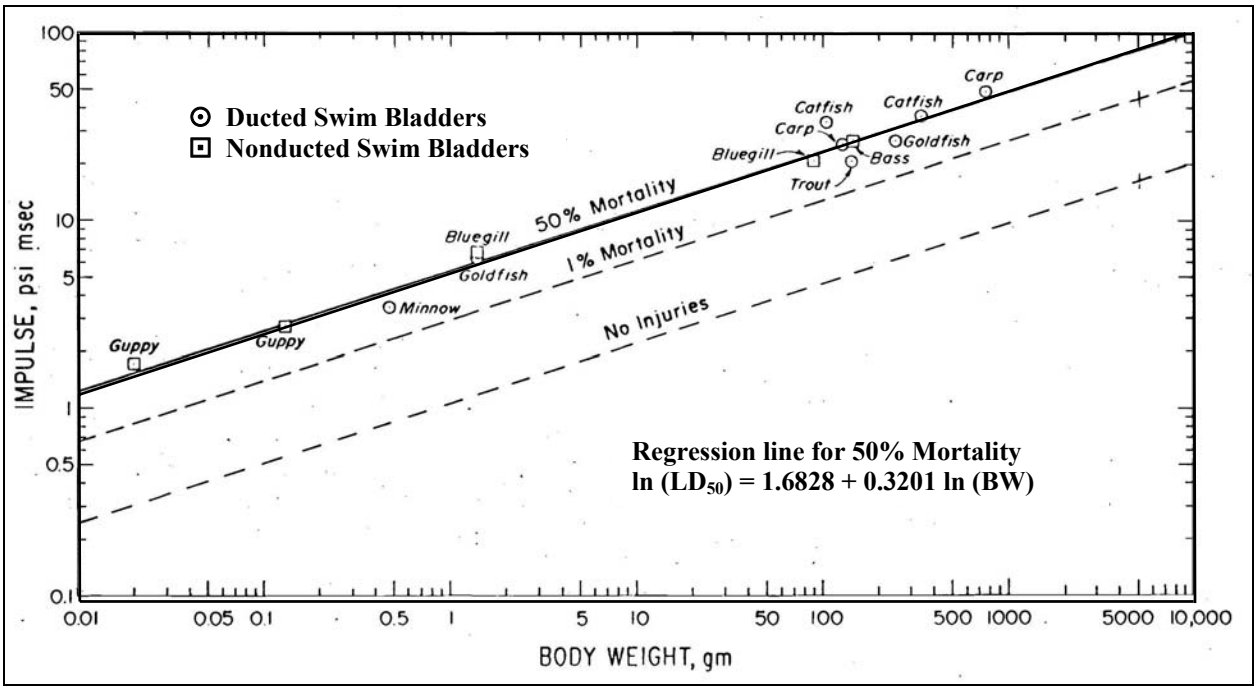


**Figure 2.** Relationship between body weight and pressure levels from detonations resulting in 1% mortality, 50% mortality, and no observed injuries. Figure from Yelverton et al. (1975).

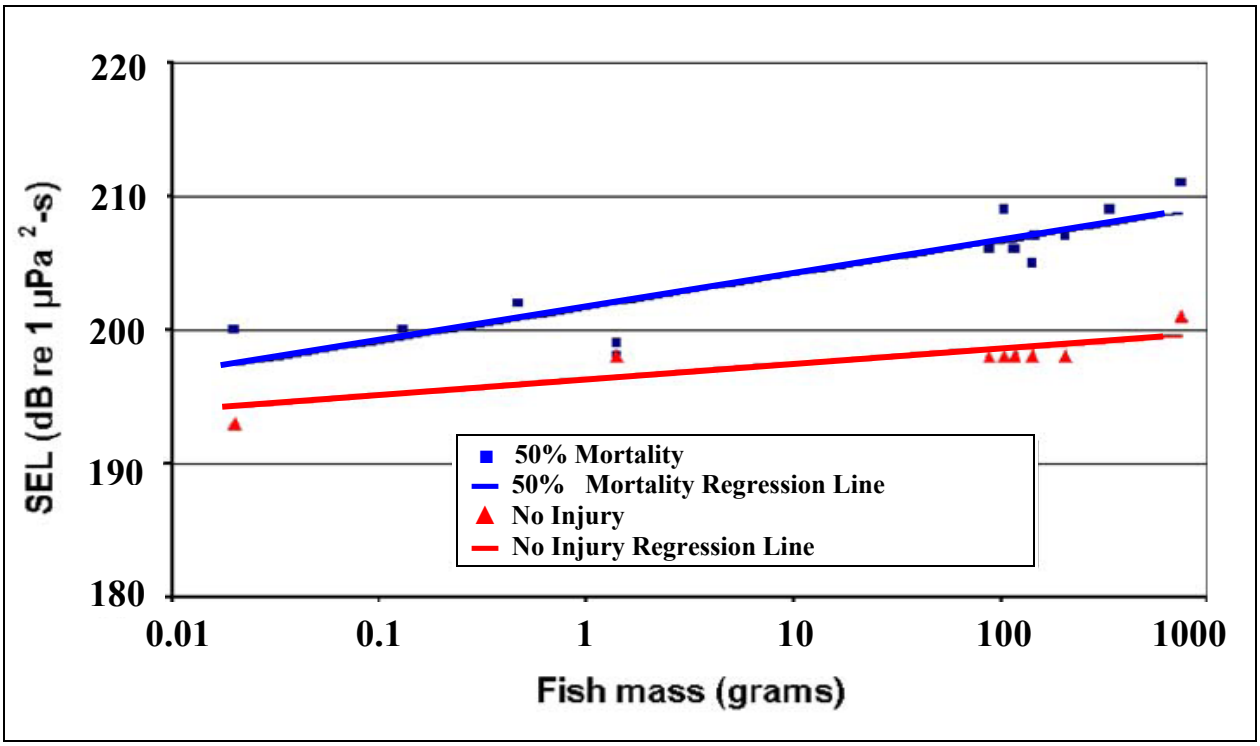


**Figure 3.** Estimated sound exposure level that results in no mortality and 50% mortality based on data for exposures to a single explosive sound as reported by Yelverton et al. (1975, see Figure 2) and modeled as an ideal impulse wave as described in Hastings and Popper (2005). Figure from Hastings and Popper (2005).

Alternative modeling methods may be used to estimate the distance of a zones of influence from a detonation when detailed information on the project or listed species are unavailable to planners and marine resource managers. In addition to the threshold criteria discussed above, the two approaches discussed below may be used to conservatively estimate impacts to protected species, when appropriate: unconfined or open-water blasts and confined blasts using stemmed charges.

**4.2. Unconfined Blasts**

Unconfined or open-water blasts include a wide variety of explosives uses for construction, demolition, and other marine projects. For unconfined blasts, precise injury zones cannot be calculated without calculating pressure measurements. These equations are considered very conservative; and, therefore, are acceptable for protected species mitigation during project planning. Young (1991) developed predictive equations based on observed safe ranges (radius) from a detonation, and be used to predict the danger zone for protected species:

$$\text{Fish Danger Zone (ft)} = 95\ (\text{fish weight in lb})^{-.13}(\text{max lb/delay})^{.28}(\text{depth of charge in ft})^{.22}$$

$$\text{Sea Turtle Danger Zone (ft)} = 560\ \sqrt[3]{\text{max lb/delay}}$$

$$\text{Calf Porpoise Danger Zone (ft)} = 578\ (\text{max lb/delay})^{.28}$$

$$\text{20-ft Whale Danger Zone (ft)} = 327\ (\text{max lb/delay})^{.28}$$

The equation to estimate danger zones for fishes is based on data from open-water blasts in shallow water. Although it is based on a limited range of conditions, the equation is appropriate for sturgeon due to their association with riverine and coastal shallow-water habitats. Although the above models are based on observed safe ranges from an explosion where no apparent injury or mortality was observed, they do not precisely predict differing levels of effects within the range between the detonation point and safe distance (e.g., the specific distances in which mortality and injury are expected are not known). However, these models are very conservative predictors to avoid serious injury and mortality. NMFS considers the equations developed by Young to be very conservative at avoiding serious injury and harassment. Although they were not developed to predict distances to avoid non-serious injury (PTS), these effects of PTS may be found within these conservatively estimated danger zones.

Many variables are often unknown in planning phases, and these models are useful for predicting safe ranges to avoid mortality when more precise harassment zone modeling cannot be completed. NMFS may request an estimation of these zones of influence for section 7 consultation under the ESA, or when applying for an incidental harassment authorization under the MMPA if determined to be necessary. In such cases, a conservative estimate of a non-serious injury and harassment zone should be estimated based upon available information from similar projects or field measurements. If sufficient information is available, a more rigorous analysis of environmental impact modeling for zones of influence should be completed.

*Example 4.2*
A hypothetical demolition project plans to remove an existing two-lane causeway and construct a new six-lane causeway over an estuarine bay. A total of 8 blast events will be conducted over a 30-day period. For one detonation sequence, a total net explosive weight (NEW) of 200 lb (60-lb, two 50-lb, and a 40-lb charge) will be detonated with three 25 ms delays between each detonation. The charges will be detonated at a depth of 20 ft to sever support structures for removal. The species occurring in the project area and information for the detonation sequence appears in the table below.

| Species in Project Area | Abundance in Bay ($\bar{x}$) | Charge Weights/Series (lb) | Max. NEW/25 ms Delay |
|---|---|---|---|
| Gulf sturgeon | 60 | 40 | 60 |
| green sea turtle | 3 | 50 | |
| Kemp's ridley sea turtle | 2 | 50 | |
| loggerhead sea turtle | 18 | 60 | |
| bottlenose dolphins | 37 | | |

Subadult Gulf sturgeon utilize the project area during the scheduled blasting activities of January-February. Subadult sturgeon foraging in the area have weights ranging from 0.7 lb to 5.3 lb (Clugston et al. 1995).

*Example Calculations*
The equations to predict the danger zone for fishes, sea turtles, and dolphins to mortality and serious injury can be solved for each species by:

$$\text{Fish Danger Zone (ft)} = 95\,(.70)^{-.13}(60)^{.28}(20)^{.22}$$
$$= 95\,(1.05)(3.15)(1.93)$$
$$= 95\,(6.38)$$
$$= 606 \text{ ft}$$

$$\text{Sea Turtle Danger Zone (ft)} = 560\,\sqrt[3]{60}$$
$$= 560\,(3.91)$$
$$= 2{,}192 \text{ ft}$$

$$\text{Dolphin Calf Danger Zone (ft)} = 578\,(60)^{.28}$$
$$= 578\,(3.15)$$
$$= 1{,}821 \text{ ft}$$

In the above example, the Gulf sturgeon danger zone (606 ft) is much smaller than that predicted for sea turtles (2,192 ft) and dolphins (1,821 ft). For sea turtles and dolphins, size of animals and depth of charge are not needed to solve the equation because they are based upon observed safe ranges. Although this may be convenient to solving the calculation, the resulting danger ranges for sea turtles and dolphins are conservatively large as a result. The danger zones predicted for sea turtles and marine mammals using these equations for explosive charges < 1,000 lb result in quite larger distances than those calculated using the energy and pressure criteria, and often

approximate, but are slightly more conservative than, harassment zones predicted by the dual criteria thresholds for TTS. However, additional distances may be needed to account for these potential effects if they are determined to be beyond the danger range.

*Visually Observable Species*
For visually observable species, the size of the area to be monitored is usually determined by the species affected over the largest area, which in the above example are sea turtles. When estimations of zones of influence are necessary using the equations developed by Young, it may be desirable to compare the zones of influence predicted with the safe range equations with similar projects that have calculated more precise zones of influence for sea turtles and marine mammals using the dual criteria thresholds (Table 1). Field measurements are desirable requirements of operation plans of common types of activities to verify the predicted zones of influence.

*Species Not Visually Observable*
The most sensitive size class is accounted for by using the lowest mass of subadult Gulf sturgeon in the area (0.70 lb). Since sturgeon cannot be effectively monitored by visual observers, physical barriers, bubble curtains, or reducing the NEW of the charge might be considered by project planners. If such measures cannot be effectively deployed, seasonal restrictions may be an appropriate measure to avoid potential mortality altogether. The Young equation is considered appropriate for Gulf sturgeon because it was developed based on data for shallow-depth, open-water explosions. In addition to their common association with shallow-water habitats, sturgeon generally spend most of their time on the bottom, where fishes are less vulnerable from open-water explosions (Young 1991), but not necessarily from buried charges. However, this open-water equation conservatively estimates safe ranges for species of sturgeon. It is important to note that as depth of the charge increases or the mass of the fish decreases, the distance of the safe range from the explosion will increase for a charge of equivalent NEW. Keevin and Hempen (1997) provide a thorough summary of other models to estimate lethal zones for fishes when additional parameters are known.

In summary, NMFS' Southeast Regional Office considers these conservative equations sufficient for mitigation planning purposes to avoid injury and mortality when more precise calculations of zones of influence cannot be completed. Additional considerations of impacts associated with non-lethal injury and harassment may be necessary, and may be dependent on the details of the project.

### 4.3. Confined Blasts Using Stemmed Charges

Confined blasts in boreholes are a method in which the explosive charge is placed in a borehole and capped with an inert material such as angular rock or crushed stone. Confined borehole blasting or stemmed charges are used primarily during channel and harbor deepening. Confined blasts increase the work done by the explosives while decreasing the amount of pressure released into the water column (Hempen et al. 2005, Nedwell and Thandavamoorthy 1992). Detonations in open water will produce both higher amplitude and higher frequency shock waves than contained detonations; thus, the technique of stemming charges results in reduced pressures and lower aquatic organism mortality than the same explosive charge weight detonated in open water (Hempen et al. 2007, Nedwell and Thandavamoorthy 1992).

The inert material must be irregularly shaped since regularly-shaped materials may be expelled during detonation and will not effectively "dampen" the blast wave. To be effective, the stemming material should be within 1/20 to 1/8 of the borehole diameter. The stemming material is not acceptable if it contains more than 10% fines (smaller than 1/20 of the borehole diameter). Stemming material should be placed at a minimum vertical length of three borehole diameters above the placed charge within sound rock or concrete. Since this approach has been based on specific measurements of underwater rock blasting projects, blasting methods that do not follow established methods for confined blasting should use an unconfined blast model to determine the appropriate impact zone or estimate zones of influence, such as that provided in section 4.2 above, or conduct field experiments to measure pressure and energy propagation from the specified blasting method so that new models may be derived.

The following equations are recommended to estimate the zone~~s~~ of influence for confined, stemmed charges (Hempen et al. 2007, Jordan et al. 2007):

**Danger Zone Radius (ft)** = $260\sqrt[3]{\text{lb/delay}}$

**Harassment Zone Radius (ft)** = $520\sqrt[3]{\text{lb/delay}}$

**Watch Zone Radius (ft)** = three times the distance of the mortality and injury zone

*Example 4.3*
Using the same blast scenario provided in example 4.2, but with confined, stemmed blasts instead of open-water, the zone of influence equations yield:

**Danger Zone Radius (ft)** $= 260\sqrt[3]{60}$
$= 1{,}018$ ft

**Harassment Zone Radius (ft)** $= 520\sqrt[3]{60}$
$= 2{,}036$ ft

**Watch Zone Radius (ft)** $= 3(260\sqrt[3]{60})$
$= 3{,}054$ ft

Based on studies to date (Hempen et al. 2005, Nedwell and Thandavamoorthy 1992), the above equation is believed to be highly conservative in estimating zones of influence for protected species, and mitigation based on this model has been tested in the field (Jordan et al. 2007). A limitation of this model, as with the above open-water blast equations, is that it does not estimate threshold levels for various types of effects from a confined blast, but estimates a conservative safe range from injury and mortality for all species. Although there would be a greater risk of mortality the closer an animal comes to the point of detonation, the distance is conservatively protective since both injury and mortality are assumed to have an equal chance of occurring if an animal were within the danger zone.

Hempen et al. (2007) estimated a mortality zone for fishes based on a low lethal level of 40 psi for stemmed charges. NMFS believes this level may be appropriate for larger size classes of fish, but not for smaller size classes (see Figure 2). If only large animals are found in a project area, the 40-psi criteria may be appropriate. NMFS recommends the equations above be used for estimating impacts to all size classes during project planning.

## 5. Assessing Impacts to Protected Species

Analytical frameworks are useful decision-making tools for protected species management. Analytical frameworks can be used to break down, or deconstruct, an activity into individual components, identify the potential effects of the noise components in the environment, and determine the level of risk posed by the noise-producing activity (Figure 4). Each noise component can be characterized by considering many factors such as the propagation characteristics of the noise, the environmental characteristics and habitat type, and species found in the area. Once all the important variables of the action and species are considered, a risk

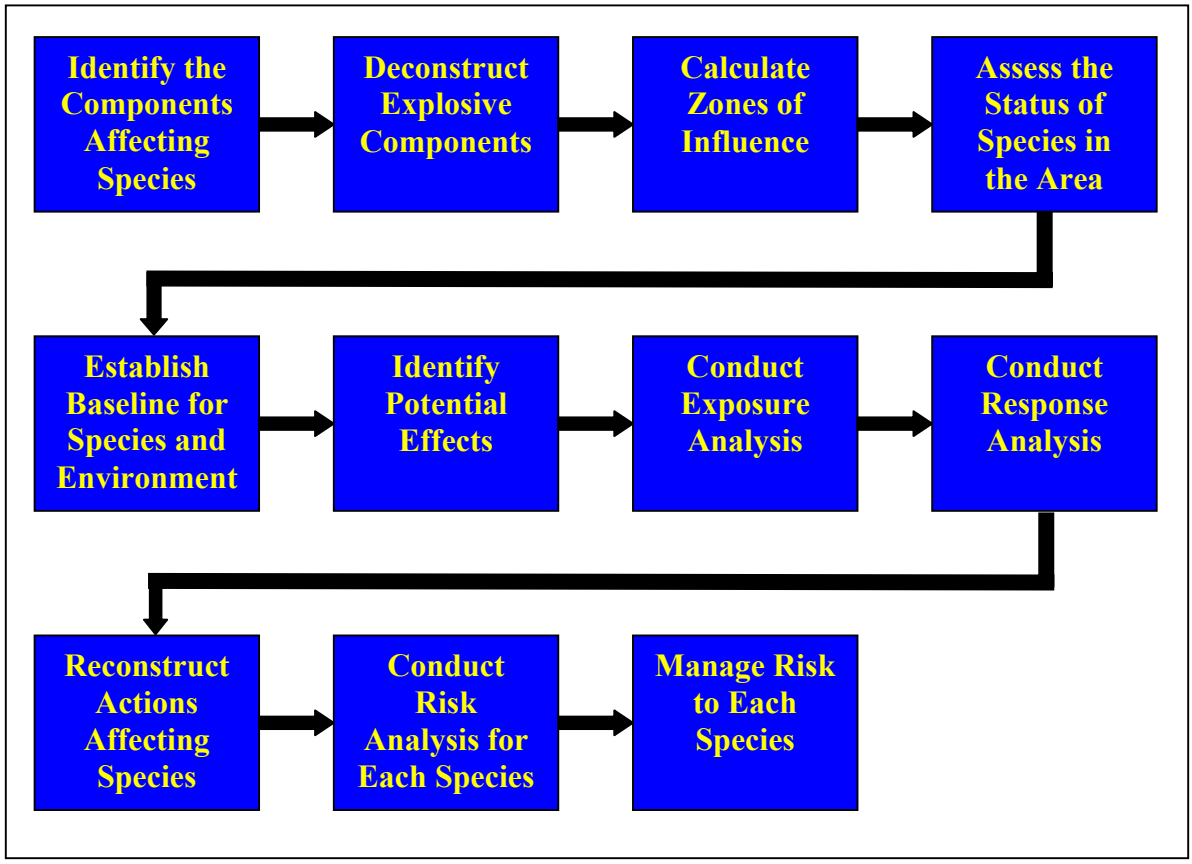


**Figure 4.** A general analytical framework to assess risk to protected species from explosions.

assessment is performed to determine the probability of undesirable effects occurring, and any measures to minimize or avoid those effects can then be considered.

Analytical frameworks utilize mathematical models or conceptual approaches to assess the potential risks to different species. The types of effects routinely considered include the potential for injury or death, the potential for harassment to occur, and habitat effects resulting from the activity. Information on any protected species in the project area is needed to properly assess any potential impacts. Information such as species abundance, animal behavior, hearing abilities, habitat characteristics, critical habitat designations, and other available information in the project area need to be considered. For example, a project can be deconstructed into its main components such as time of year, project duration, charge weights, number of explosions per day, and other variables (see *Summary of Information Needed* section below). Noise from the project can further be deconstructed into pressure units (psi) and dB units (EFD). Using the threshold criteria or models discussed in previous sections, zones of influence can be calculated to determine probable effects to protected species or critical habitat. For any effects that need mitigating, a number of different mitigation tools may be used to avoid or minimize impacts to protected species and their habitats.

*Information Needed to Assess Impacts*

A complete description of the activity and an assessment of impacts to protected species from explosives should be submitted with a request for consultation or incidental take authorization to NMFS. NMFS may also consider other actions associated with the use of explosives that may affect protected species such as vessel traffic, dredging, construction noise, effects on habitat quality, and other potential effects of the action. Any additional activities that may result in impacts to protected species or those identified in consultation with NMFS should also be identified. An analysis of all activity components that may affect protected species should be conducted, and those resulting in potentially adverse affects identified. For explosives use, a detailed blasting plan should be submitted with, or integrated within the impact analysis for a particular activity. The information needed for NMFS to assess activities using explosives includes:

- A description of the types of targets or structures on which explosives will be used;
- The type of explosives used;
- Details of the use of delays, stemming, charge placement, and depth of detonation;
- The total number of detonations or detonation sequences for the project, and number per day;
- The maximum explosive weight detonated per 25 ms period for each detonation sequence;
- The number of delays used and delay time for each detonation sequence;
- The time of year (months) the blasting is planned; and
- The total number of days blasting is expected to occur;
- A description of habitat in which explosives will be used including depth, salinity, water temperature, substrate type, and biota;
- A description of protected species and habitat in the project area;
- A summary of potential effects to species and habitat from the activity;

- An estimation of the zones of influence to protected species indicating the method by which they were calculated. Models and mitigation methods may be approved on a case-by-case basis, or as new information becomes available regarding blast modeling or exposure criteria for protected species;
- An analysis of effects to protected species;
- An analysis of effects on protected species habitats and primary constituent elements (PCEs) of any critical habitat, if designated in the project area;
- A proposed mitigation/monitoring plan for the project; and
- Observer qualifications

A well-prepared blasting plan can partially fulfill the recommendations for biological assessments (BAs) and environmental assessments (EAs). Guidelines on the preparation of a BAs and EAs, and information regarding section 7 consultation can be found on the Southeast Regional Office web site at http://sero.nmfs.noaa.gov/pr/pdf/BA_guide_comboeh081105.pdf.

Information regarding applying for an incidental take authorization under the Marine Mammal Protection Act may be found at http://www.nmfs.noaa.gov/pr/permits/incidental.htm.

**6. Measures to Reduce the Risk of Harm to Protected Species**

Environmental mitigation should be a part of every blasting plan and include appropriate measures identified in the risk assessment for the species and habitats found in the project area. For common activities requiring explosives, such as oil and gas structure decommissioning, some standard recommendations have been developed in coordination with NMFS. A "suite" of measures that applies to all the protected species found in a project area is desirable for flexibility in project planning, as well as for species-specific management needs. Because fish are not readily observable, visual surveys alone cannot avoid impacts; therefore, additional mitigation should be considered when protected species of fish are present in a project area. The suite of measures below should be considered when preparing protected species mitigation measures for blasting plans. Implementation of these measures does not necessarily ensure that all impacts will be avoided. Project-specific recommendations may be discussed during consultation with NMFS.

1. Establish zones of influence based upon protected species found in the project area, using an appropriate model.

2. The lowest NEW per detonation should be used to complete the work for a particular construction, severance, or demolition activity. Using smaller NEWs is associated with smaller impact zones where protected species (listed species and marine mammals) could be harmed. Shaped and fracturing charge designs are being developed and refined by the demolition industry that increase the efficiency of the work, resulting in smaller NEWs than for "bulk" charges. Water gel explosives have a lower detonation velocity, generating less shock energy than some other high-detonation velocity explosives (e.g., dynamite) and have lesser impacts on aquatic animals.

3. The use of delays should be maximized between individual blasts to separate the total NEW into a blast episode, creating a series of discrete, consecutive blasts. A blast episode consists of a single blast or a series of blasts that are detonated with a delay to lower the overpressure at a received distance in the environment. Discrete detonations using delays effectively reduce the zones of influence. For delay intervals less than 25 milliseconds (ms), NMFS recommends that zones of influence for protected species be estimated by calculating the distances for the summed explosive weight detonated per 25 ms period.

4. The use of bubble curtains, physical barriers, and other mitigation techniques to dampen the shock wave from detonations should be considered. The effectiveness of mitigation techniques may vary depending on the environment (e.g., currents and water depth), number and NEW of the explosives used, and other project details. Bubble curtains dampen or attenuate the sound transmitted through the bubble curtain. A bubble curtain for explosives may consists of shock-resistant materials at various depths and distances from an explosion. The bubble curtain should be effective at reducing pressure to levels below those resulting in harm to the species found in the project area.

5. The perimeter of impact zones should be established and demarcated (e.g., with landmarks or brightly colored buoys) for visual reference when conditions permit. Land- or ship-based observations may use binoculars and the naked eye to monitor the zones of influence. Fixed focus, vector binoculars are useful to establish distance from the project site and identify species. When aerial surveys are proposed, an aerial survey plan should be submitted to NMFS for approval with the mitigation plan.

6. Qualified observers should be used that have completed an approved training program to monitor the zones of influence. Each observer should be equipped with a two-way radio dedicated to protected species communication, polarized sunglasses, binoculars, a red flag or other backup communication, and any necessary data recording equipment.

7. Monitoring should be conducted from the highest vantage point(s) and/or other locations that provide the best, clear view of the entire zone of influence. These vantage points may be on the structure being removed or on nearby surface vessels such as crew boats.

8. A sufficient number of observers should be used to effectively monitor the established zones of influence under variable charge sizes and environmental conditions. The number of observers used may be dependent on numerous factors including whether aerial or vessel/shore-based observations are used, the size of the zones of influences, distance from shore, sea state, and observer fatigue.

9. For large zones of influence, or to augment visual observations, passive acoustic monitoring may be utilized to detect vocal species of marine mammals when animals are not readily observable at the surface. However, passive listening should not be used as a replacement for an adequate number of visual observers.

10. If divers are used during the demolition, they should be instructed to scan subsurface areas around the removal site for the presence/absence of protected species during the course of removal operations.

11. The chief observer should have authority to immediately halt activities should a protected species be observed within the impact zone, or is in the watch zone and in imminent danger of injury by heading toward the impact zone.

12. Surveys should be conducted before and after each blast episode. The duration and method of surveys should be determined in consultation with NMFS. Post-detonation observations are to start at the removal site and proceed in the direction of wind and current movement from the blast location.

13. Surface and/or aerial protected species surveys should be conducted in environmental conditions adequate for effective visual observation. Aerial surveys should be conducted during daylight hours and cease when marine conditions are not adequate for visual observations, or when the pilot/removal supervisor determines that helicopter operations must be suspended. Detonations should be delayed until conditions improve sufficiently for monitoring to be effectively completed.

14. When a protected species is sighted or heard within the impact zone, detonations should be postponed until it is verified to be outside of the impact zone.

15. Blasting should be limited to daylight hours (between one hour after sunrise and one hour before sunset). If pre-detonation and post-detonation surveys are to be conducted, pre-detonation surveys shall not begin prior to sunrise and detonations must not occur if the post-detonation survey cannot be concluded prior to sunset.

16. Detonation of scare charges to intentionally harass sea turtles or marine mammals into leaving a project area is prohibited. Scare charges using detonation cord are potentially harmful to fishes (California Department of Fish and Game 2002) if the mass of the explosives is not considered. In some cases, scare charges may be necessary to reduce the risk of mortality to sturgeon and smalltooth sawfish in the immediate area of a blast. Detonation caps not exceeding 0.5 g (Collins et al. 2001) may be approved on a case-by-case basis for use as scare charges for sturgeon and smalltooth sawfish. Scare charges not exceeding 0.5 g are also recommended to avoid the attraction of marine mammals, sea turtles, and piscivorous fishes that are stunned or wounded by the scare charge.

17. All protected species entering the impact zone should be allowed to move out of the area under their own volition. Enticing marine mammals to bow-ride or intentionally harassing animals into leaving the area is prohibited.

18. All “shock-tubes" and detonation wires should be recovered and removed after each blast.

19. The chief observer should submit a post-project report within 30 days of completion of the project to the permitting agency. The report should include project information, including but not limited to, a description of the project and explosives used, survey information, environmental conditions, and observations of protected species. Reports should be available to NMFS upon request.

20. Report dead or injured protected species to your local stranding network contacts. A list of sea turtle stranding responders is available at http://www.sefsc.noaa.gov/seaturtleSTSSN.jsp.
    A list of marine mammal stranding network responders for each state is available at http://www.nmfs.noaa.gov/pr/health/networks.htm or may be reported to the marine mammal stranding hotline at 877-433-8299.
    All other dead or injured protected species should be reported to NMFS' Southeast Regional Office by telephone at (727) 824-5312, or by FAX at (727) 824-5309.

*Additional Considerations*
The following mitigation measures may be recommended under some circumstances to avoid impacts to important habitats and behaviors of protected species.

1. Avoid blasting techniques in regions that may affect any primary constituent elements of critical habitat designated for a listed species.

2. When blasting in inshore habitats, blasting should be conducted at low tide, above the water line to reduce the transmission of energy into the water column.

3. Sequence work to minimize impacts to biologically important areas such as migration corridors, important foraging areas, spawning habitats, near nesting beaches, calving areas, or in juvenile or developmental habitats protected species. These considerations may involve temporal or seasonal considerations when blasting in biologically important habitats.

4. No debris from the blasting operations should be left on the seafloor unless the structure is to be decommissioned as an artificial reef. The amount of debris scattered by blasting should be minimized to the greatest extent practicable (e.g., the use of blast mats). Methods should be used to minimize benthic and habitat disturbances such as removing structures below the mudline, use of blasting mats, and removing debris off the seafloor with appropriate methods, and in consultation with NMFS.

## 7. Recommended Areas of Future Research

NMFS has identified the following recommendations for needed research areas that would further our understanding of the effects of explosives on protected species, and mitigation of those effects. Federal action agencies involved with explosives use should consider these recommendations during project planning, monitoring of mitigation effectiveness, and consideration of applied research projects when evaluating the environmental impacts of projects requiring explosives.

1. The development of a model based on an exposure/response approach would be a useful tool for planners and managers to estimate different levels of impacts to protected species. Using the available scientific information, development of more dynamic models and/or software programs for various scenarios of explosives use (e.g., substrate type, water depth, charge size, depth of charge, species, species behavior (e.g., water column preference or dive patterns, and size of an animal) to develop a more predictive planning and evaluation tool.

2. Field verification of the peak pressures and sound exposure levels associated with different explosives uses are needed to develop more accurate models for different common uses of explosives. Common construction and demolition projects using explosives in the southeast U.S. include transportation uses (e.g., removal of bridges and causeways), oil and gas structure removal, harbor creation or maintenance, as well as other activities. Additional studies are also needed on shock wave propagation through different structures at varying depths, such as those constructed of concrete, steel, and charges buried beneath the seafloor.

3. Development of a more accurate model to estimate zones of influence for sea turtles based on expected injury, rather than observed safe ranges, is needed to better from predict the effects of explosives.

4. Studies to measure the peak pressure and sound exposure level produced from multiple pathways of shock waves produced from a detonation series are needed to estimate impacts to protected species. Field measurements to evaluate the pressure levels produced from different times set between detonations are need to verify the effectiveness of using delays and decking.

5. Development, testing, and field verification of new explosives techniques that reduce the peak pressure of the shock wave and associated zones of influence should be conducted.

6. The development and verification of new mitigation and monitoring techniques are needed to lessen the impact on protected marine resources.

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