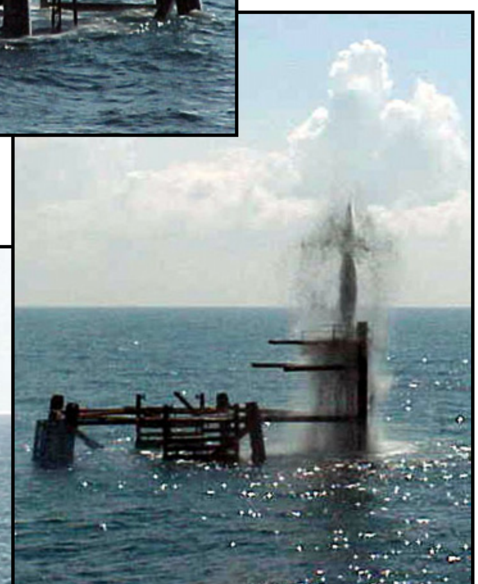
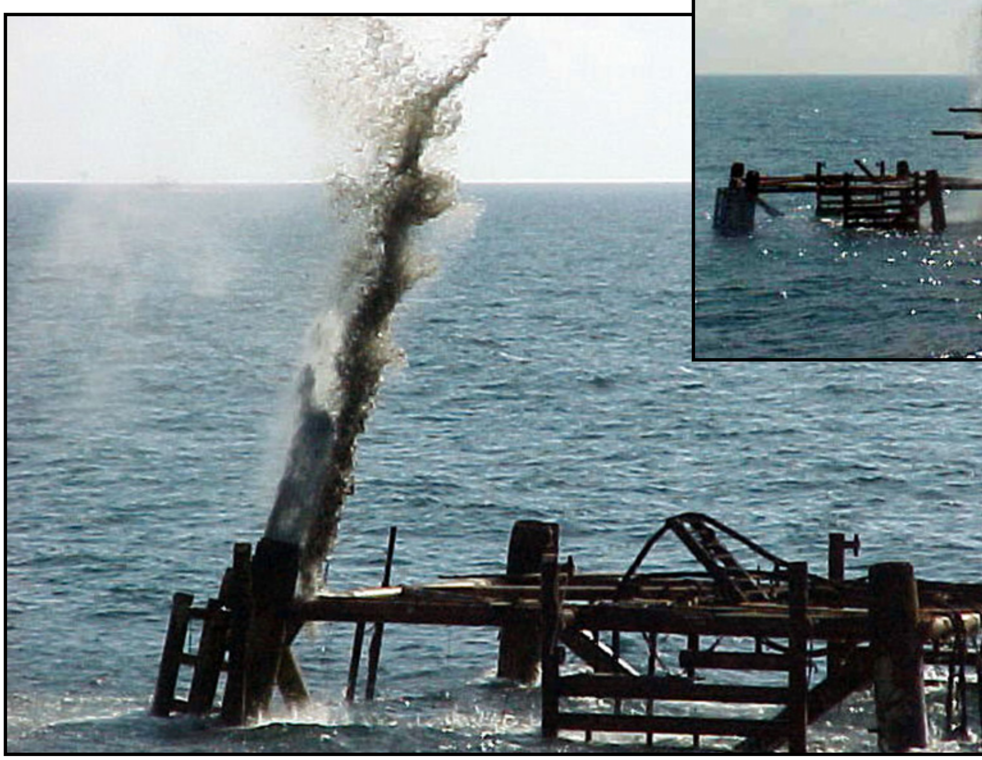
OCS Study
MMS 2003-070

Explosive Removal of Offshore Structures

Information Synthesis Report





U.S. Department of the Interior
Minerals Management Service
Gulf of Mexico OCS Region

OCS Study
MMS 2003-070

Explosive Removal of Offshore Structures

Information Synthesis Report

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LIST OF ACRONYMS

ABR	auditory brainstem response
ANFO	ammonium nitrate with fuel oil
AUV	autonomous underwater vehicle
CFR	Code of Federal Regulations
CSA	Continental Shelf Associates, Inc.
EA	Environmental Assessment
EFD	energy flux density
EIS	Environmental Impact Statement
ER	Environmental Report
ESA	Endangered Species Act
FAD	fish attraction device
LOA	Letter of Authorization
MMPA	Marine Mammal Protection Act
MMS	Minerals Management Service
NEPA	National Environmental Policy Act
NMFS	National Marine Fisheries Service
NOAA-F	National Oceanic and Atmospheric Administration – Fisheries Division
NTL	Notice to Lessees
OCS	outer continental shelf
ONR	Office of Naval Research
PBI	primary blast injury
PI	Principal Investigator
PTS	permanent threshold shift
QRB	Quality Review Board
RDX	cyclonite
RL	received level
rms	root-mean-square
ROV	remotely operated vehicle
SEL	sound exposure level
SL	source level
SPL	sound pressure level
TL	transmission loss
TNT	trinitrotoluene
TTS	temporary threshold shift

CHAPTER 1
EXECUTIVE SUMMARY

ES-1 Background, Objectives, and Study Methods

Nearly 4,000 oil and gas structures currently exist in Federal waters of the U.S. outer continental shelf (OCS), with the vast majority present in the Gulf of Mexico. The primary purpose of these structures (e.g., fixed platforms) is to develop and produce oil, natural gas, and gas condensates from offshore hydrocarbon reservoirs. When offshore production from a producing field becomes uneconomic, the lease(s) may be terminated by the operator. As one of its lease conditions, the Minerals Management Service (MMS) requires that operators (responsible for installation and operation of a platform) subsequently remove the structure within a year of lease termination.

Offshore structure (e.g., platform) removal typically involves the use of explosives to sever structure-associated components requiring removal – wellheads, piles, etc. – several feet below the seafloor. Historically, offshore development and production of oil and gas reserves has occurred in shelf waters (i.e., <200 m). Movement of production platforms farther offshore, coupled with recent interest in deepwater development, however, has raised the issue of future platform removal in deeper OCS waters (e.g., over the continental slope). Further, the presence of listed (i.e., endangered or threatened species listed or proposed for listing under the Endangered Species Act [ESA]) and/or protected species (i.e., all marine mammals are protected under the Marine Mammal Protection Act [MMPA]) in marine waters, coupled with the mandate to minimize or eliminate the potential for impact to these species, underscores the need to fully understand the environmental impacts associated with explosive platform removal.

The focus of the present study was to collect and synthesize existing information relevant to explosive removal of offshore structures in aquatic environments. While the expected application of this knowledge may include U.S. waters (e.g., Gulf of Mexico, California, and Alaska OCS), the scope of this effort is worldwide. Sensitive marine resources considered in this analysis include marine fishes, marine turtles, and marine mammals. The primary study objectives were to:

1) provide a summary of available information by topic;
2) identify information and data gaps that could be filled by subsequent research activities; and
3) recommend areas of research to meet MMS information needs.

The study effort was divided into two separate tasks – to develop the information synthesis report, and to create a separate electronic database of all identified data sources. Information gathered included pertinent data sources in the following topics:

- Explosive Removal Methods;
- Physics of Underwater Explosions;

- Biological Resources;
- Impacts to Biological Resources; and
- Mitigation and Monitoring of Effects.

Information was gathered via electronic database searches (e.g., via DIALOG Information Retrieval Service; access to 14 separate databases) and review of corporate and personal libraries of project Principal Investigators, and included data sources from the peer-reviewed literature, conference and workshop proceedings, contract reports, and the gray literature.

ES-2 Decommissioning and Explosive Removal Methods

To remove a fixed platform, the installation steps are essentially reversed. Topside equipment such as living quarters, generators, and processing equipment is taken off by crane and returned to shore for scrap or to be reused. The deck sections are then lifted from the platform and placed on cargo barges for transportation to their disposal site. Conductors, flare piles, well conductors, submerged wells, and caissons are structures subject to explosive removal. MMS regulations require that the piles and well conductors be severed at least 5 m (15 ft) below the mud line and removed.

Pilings and conductors can be cut manually by a number of mechanical means including:

- use of tungsten-carbide blade cutters contained in routine rig workover equipment;
- use of diamond wire and hydraulic shear cutters deployed by remotely operated vehicles (ROVs); and
- manually by divers through the use of mechanical or abrasive cutting techniques.

The safest and easiest cutting procedure is to place an explosive charge inside the piling at the desired depth and sever the piling explosively. Presently employed explosive cutting techniques include the following:

- Bulk Explosive Charges – the most commonly used technique for explosive cutting of piles and conductors; comprising C-4 or Comp B explosives; explosives are castable and moldable, have a high velocity on detonation and a high shattering power, and are not as dangerous to handle as some other types of high explosives. Bulk charges are lowered into prepared pilings or well conductors and detonated nearly simultaneously with a 0.9-sec delay in groups of eight or less. Bulk explosives have a 95% success rate when sized properly. Increased water depth has no adverse impact on the success rate of bulk explosive cuts.

- Configured Bulk Charges – configured bulk charges such as “ring charges” and “focusing” charges are designed to collide or “focus” the detonation front to concentrate more energy along the fracture line, and thus reduce the size of the charge needed to cut a piling. These types of charges have been effective in reducing “belling” or bulging out of the severed piling.
- Cutting Charges – cutting charges include linear-shaped charges and “cutting tape.” Linear-shaped charges use high-velocity explosive energy to accelerate a v-shaped band of cutting material, usually copper, in a high velocity jet that penetrates through the steel of the piling. Explosive cutting tape is a flexible version of the linear-shaped charge.

A series of potential future explosive cutting techniques also was evaluated, including contact plaster charges, shock-wave focusing charges, and radial hollow charges.

Underwater explosive source characteristics were detailed, including the physics of the explosive process, the use of shaped charges and associated directionality of the explosive-based shock wave, media considerations (e.g., open water detonation), the use of multiple charges, and shock waves and acoustic propagation.

ES-3 Sound Metrics and Injury-Mortality Criteria

Metrics

Sound level metrics are parameters that quantitatively describe the characteristics of sound pressure waves at a given spatial location. The commonly used metrics for impulsive sounds describe the amplitude, energy, and time-related characteristics of the pressure wave. The values of specific metrics are used to gauge the degree of impact that underwater sound signals have on marine wildlife. Standard thresholds for the metrics have been established in reference to the minimum levels at which specific impacts have been observed to occur for a given species.

The metrics that need to be considered for gauging one type of impact may differ from the metrics used for another type of impact. The most common metrics for impulsive sounds are as follows:

- Peak Pressure – The highest pressure attained by a sound pressure signal. This pressure is measured with respect to ambient pressure, and is also referred to as zero-to-peak pressure.
- Peak-to-peak Pressure – The difference between the highest pressure and lowest pressure over the duration of a waveform. For impulsive sounds produced by blasting, the lowest pressure is generally negative with respect to ambient pressure and occurs soon after the largest positive peak due to expansion imparted to the water by its positive impulse.
- Impulse – The time integral of pressure through the largest positive phase of a pressure waveform. It has units of Pascal seconds.

- Root-mean-square (rms) – The square root of the mean square pressure over the duration of the impulsive waveform. The duration used strongly influences the value of this metric, though its definition is sometimes quite ambiguous. Recent methods have been proposed for determining the duration based on the cumulative energy flux density function.
- Energy Flux Density (EFD) – The total acoustic energy propagated through a unit area normal to the direction of propagation. The EFD of plane waves can be computed as the time integral of squared pressure, divided by the acoustic impedance of the medium. The EFD is not suitable for continuous-wave sounds because the integral is not normalized in time. The EFD has units of Joules/m^2, but is commonly expressed in decibels (dB).
- Sound Exposure Level (SEL) – The time integral of square pressure divided by the product of sound speed and water density. The sound exposure level is commonly expressed in decibels.

Decibels

All of the above metrics, except for impulse, are normally expressed in decibels. The decibel presents pressure values on a logarithmic scale relative to a pre-defined reference level. The EFD and SEL metrics are converted to decibels in a slightly different way. It is noteworthy that these 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.

Frequency Content

None of the above metrics directly provides information about the spectral energy content of the sound signal. Spectral content is important for some types of impact criteria (e.g., the accepted threshold level for temporary threshold shift [TTS] is based on exceeding EFD levels of 182 dB re $\mu Pa^2 s$ in any 1/3-octave frequency band). The standard approach in this case is to apply frequency domain filtering to the pressure waveform prior to computation of the threshold. This approach is recommended only for the EFD (or SEL) and rms metrics. A modified version of the peak pressure metric also has been developed that accounts for the frequency-dependent hearing sensitivities of specific species – identified as dB_{ht}(Species).

dB_{ht}(Species*)*

As a means of assessing potential injury from acoustic sources, the concept of dB_{ht}(Species) was summarized. The dB_{ht}(Species) metric expresses sound pressure levels relative to the hearing thresholds of specific species. It is used most commonly for gauging impacts of continuous sounds, although it may also be applicable for impulsive noise. This metric is based on the same principle as frequency weighting schemes used for determining impacts of noise on humans. Measurements of hearing sensitivity versus frequency for individual species, known as audiograms, have been measured for many species of fish and a limited number of whales. Confidence in the accuracy of audiograms for most marine species is, however, limited at the present due to the small number of individuals upon which these measurements have been performed.

Impulse

Impulse is defined by the time-integral of pressure through the waveform. The impulse for exponentially decaying shock pulses from underwater explosives (assuming no interference with surface or bottom reflections) is given by a simple expression. However, for shallow sources or receivers, the arrival of the surface reflection has the effect of canceling later parts of the pressure pulse. Consequently, impulse calculations are often performed by integrating the direct path pressure only up to the arrival time of the surface reflection.

Root-Mean-Square Levels

The rms sound level metric has gained popularity because it gives the most representative measure of the average effective amplitude over a transient signal's duration. This metric is especially well suited to characterizing sonar pings and signals such as windowed sine pulses. It also is quite widely applied for estimating impacts of impulsive airgun noise on marine mammals. The rms metric is computed as the square root of the mean squared pressure over the signal's "duration," the definition of which is somewhat ambiguous.

ES-4 Affected Environment

The affected environment discussion considers those components of the biological environment that are at the greatest risk of impact from explosive platform removal – marine fishes, marine turtles, and marine mammals. In the development of this text, emphasis has been placed on the presence and characteristics of species present in U.S. waters. Particular emphasis has been placed on listed and/or protected species – those protected under the ESA and MMPA, respectively.

Marine Fishes

In the three OCS regions (i.e., Gulf of Mexico, Pacific, and Alaska), large numbers of fishes associate with oil and gas structures. These fishes are briefly characterized, with emphasis on federally managed species. Major findings pertinent to marine fishes, by region, include:

- Gulf of Mexico OCS – reef and pelagic fishes that associate with oil and gas platforms are broadly classified into coastal, offshore, and bluewater assemblages.
- Pacific OCS – fishes that associate with offshore oil and gas structures and are generally classified as groundfishes, including >70 species, most of which are rockfishes.

- Alaska OCS – no information on platform-associated fishes was identified for the primary offshore oil and gas field – Cook Inlet. Other platforms and structures in the Beaufort Sea are built upon large gravel causeways or berms and will not be removed with explosives.

Marine Turtles

Seven marine turtle species were considered in this analysis. Six species are listed as either endangered or threatened under the ESA (i.e., loggerhead, green, hawksbill, Kemp's ridley, Pacific [olive] ridley, and leatherback), while the seventh (i.e., black turtle) is currently unlisted. The distribution of marine turtles species within MMS OCS Planning Areas is variable. Two marine turtle species – loggerheads and leatherbacks – are known from all three regions (Gulf of Mexico, Pacific, Alaska), and are the only marine turtle species present in Alaska waters. Remaining species are found exclusively in their respective regions, including green, hawksbill, and Kemp's ridley in the Gulf of Mexico region, and black and Pacific (olive) ridley in the Pacific region.

Marine Mammals

Marine mammal summaries were organized by OCS Region – Gulf of Mexico, Pacific, and Alaska. Marine mammal data have been compiled and summarized based on both historical and recent aerial and/or shipboard surveys, with the focus placed on those areas within each region where oil and gas platforms or other OCS facilities have been placed and will require removal.

All marine mammals are protected by Federal law (MMPA), which affords individuals and populations from mortality, injury, or harassment. Under MMPA, a species may be designated as a depleted or strategic stock. In addition, individual species also may be designated as threatened or endangered under the ESA. A stock may be classified as threatened or endangered, depleted, and strategic simultaneously.

In the Gulf of Mexico, toothed whales are by far the most abundant marine mammals present. No pinnipeds are found in the Gulf of Mexico, and Bryde's whale is the only mysticete that is seen with any regularity. Sixteen species are routinely sighted in the Gulf of Mexico, and most are year-round residents. Bottlenose dolphins and Atlantic spotted dolphins are by far the dominant species of the continental shelf and shelf edge. Bottlenose dolphins also can range onto the continental slope in the northeast Gulf. The most abundant species in deep water are *Stenella* spp. dolphins. Bryde's whales have been found in the northeastern Gulf along the 100-m contour.

In the Pacific OCS, numerous marine mammal species are resident or transitory. Thirty-three species of cetaceans may occur in the Southern California Bight, including 25 species of toothed whales and 8 species of baleen whales. Common toothed whale species include Dall's porpoise, Pacific white-sided dolphin, Risso's dolphin, short-beaked common dolphin, northern right whale dolphin, and gray whale. Other species occur in relatively moderate or small numbers or are only occasionally sighted.

ESA-listed species off southern California include sperm, northern right, humpback, blue, fin and Sei whales. Six species of pinnipeds may also occur in southern California waters (i.e., harbor seal, northern elephant seal, California sea lion, Steller sea lion, and northern and Guadalupe fur seals). The southern sea otter is the only fissiped known to occur in the waters of southern California.

In the Alaska OCS, oil and gas production activities in Federal waters have historically been restricted to two separate regions – Cook Inlet and nearshore waters of the Beaufort Sea. Platform removal is only expected to occur in the Cook Inlet (i.e., only gravel islands are used for offshore oil and gas production on the Beaufort Sea shelf). Marine mammals documented during recent surveys in Cook Inlet include beluga whales, harbor seals, Steller sea lions, and the sea otter, while humpback and fin whales were also reported along the southern limits of the inlet. Other cetaceans that can occur in the area but were not observed during recent surveys include killer whale, harbor porpoise, Dall's porpoise, Pacific white-sided dolphin, gray whale, minke whale, Baird's beaked whale, and Cuvier's beaked whale. In addition, sperm, Sei, right, and blue whales may wander into the area. Three other pinniped species – northern fur seal, northern elephant seal, and Pacific walrus – also may occur in Cook Inlet.

ES-5 Discussion and Recommendations

Major chapters of the synthesis report have reviewed the different technologies used for explosive structure removals, the physics of underwater detonations, and potential impacts on marine fishes, marine turtles, and marine mammals. The discussion chapter discusses the findings, identifies data gaps, and recommends topics where further study would be appropriate.

This report has focused on three faunal groups: marine fishes, marine turtles, and marine mammals. Marine turtles and marine mammals are federally protected species for which death or injury of individual animals is a serious concern. In contrast, although many fish species associated with offshore platforms are federally managed, impacts on stocks or populations are the main concern, rather than death or injury of individuals. While mitigation and monitoring requirements have been established for marine mammals and turtles, there are no measures specifically developed to protect marine fishes; rather, it is assumed that fish kills are unavoidable during explosive structure removals.

Environmental data concerning platform removals serve two main purposes: 1) to allow impacts to be estimated (e.g., numbers of animals that may be killed or injured during structure removals); and 2) to aid in developing or refining mitigation measures that prevent or reduce the likelihood of impacts. Sources of data have included laboratory and field experiments, modeling studies, and anecdotal field observations. There are important differences among the three faunal groups discussed in this report with respect to the types and adequacy of data available (**Table ES.1**). In general, marine fishes are the best-studied group, and sea turtles the least studied.

Table ES.1

Types and Amounts of Data Available Regarding Impacts of
Underwater Detonations on Marine Fishes, Marine Turtles, and Marine Mammals

Group	Types of Data Available		
	Experimental Studies	Modeling	Anecdotal Observations
Marine Fishes	Numerous lab and field studies of explosive effects. Quantitative studies following actual structure removals.	Extensive.	Many observations (e.g., fish kills).
Marine Turtles	One study with caged turtles during platform removal (but no pressure measurements).	Very limited.	Mortalities, injuries, strandings following detonations.
Marine Mammals	Recent studies of explosive effects on dolphin carcasses. A few auditory effects studies but most not for explosives. Several studies on behavioral effects of seismic sources but limited relevance.	Limited efforts, mostly connected with ship shock trials; some models used data from terrestrial mammals.	Mortalities, injuries, strandings following detonations.

Marine Fishes

Lethal effects of underwater explosions on numerous species of fishes have been studied in laboratory and field experiments and have been modeled extensively. These data and models have been used to calculate effect ranges. In addition, there have been studies specifically designed to estimate fish kills associated with structure removals in the Gulf of Mexico.

One set of calculations reviewed predicts effect ranges varying from 12 m for non-swimbladder species to 230 to 349 m for swimbladder species. Actual observations following structure removal detonations indicate most dead fishes were within 25 m, with numbers declining with distance out to 100 m. Other surveys have shown that fish densities around platforms are highest within a horizontal distance of 18 to 50 m from the structure. Therefore, it seems that most fishes associated with platforms are close enough to be killed or injured by a typical underwater detonation associated with structure removals. Of course, there are many variables affecting the fate of individual fishes including their size, shape, vertical position in the water column, and orientation relative to the detonation source.

The main goal with respect to fish populations is predicting impacts rather than setting “safety ranges” for mitigation/monitoring. For predicting impacts, the empirical data from observations during actual structure removals would seem to be more useful than any attempt to calculate impacts based on experiments and models. Huge variations in the fish population itself, including numbers, species, sizes, and orientation and range from the detonation, would make it very difficult to accurately predict mortalities at any specific site. Since the data collected by several researchers are limited in terms of depth range and geographic extent, additional studies may be needed to predict impacts in other areas, including deepwater environments.

Marine Turtles

There have been no laboratory studies of explosive impacts on marine turtles, and only limited field observations and experiments. In several instances, turtle injuries and mortalities (and in some cases, strandings) have been noted following underwater detonations. In one case where turtles were recovered after an open-water detonation, both charge weight and the approximate distances of the turtles from the detonation were known. Only one field experiment has been conducted in which marine turtles were exposed at known distances from a structure removal detonation; however, that study did not include concurrent pressure measurements to estimate the magnitude and duration of the shockwave received by the caged turtles. There have been several anecdotal reports of turtle deaths or strandings following structure removal detonations, including a few in the 15 years since the current mitigation/monitoring requirements were instituted.

There have been no mechanistic models developed specifically to estimate impacts on marine turtles. Rather, it has been assumed that models developed for other vertebrates are reasonable approximations. Several researchers developed an equation for a turtle "safety range" based on field observations of three turtles following an open-water detonation. The equation is simply based on cube-root scaling of the charge weight and the distance at which one turtle apparently was not affected. More recently, another researcher has provided a more conservative version of the same equation but states that it is based on the criteria for platform removal established by the National Marine Fisheries Service (NMFS) – i.e., it was not independently derived from observations or experimental data. Recent environmental assessments have also included modeling to establish effect ranges using earlier turtle death/injury observations and a lung injury model. The results suggest that lung injury predictions for marine turtles are not inconsistent with predictions for small mammals.

An important goal with respect to marine turtles is calculating the areal extent of the mortality/injury zone so that this area can be monitored for turtles prior to detonations. In the 1988 "generic consultation" for structure removals in the Gulf of Mexico, the NMFS specified that the area within 3,000 ft (914 m) of the platform must be clear of visible marine turtles prior to detonation. The NMFS document does not specify the source of this number, but apparently it is based on the turtle death/injury observations to date rather than any modeling.

Years of experience using the 3,000-ft (914-m) range monitored under the "generic consultation" suggest it has been effective in preventing most deaths or serious injuries of marine turtles. In addition, the modeling analysis done during recent ship shock environmental assessments, while not directly addressing the "safety range" for structure removals, suggests that the monitoring range specified in the "generic consultation" is likely to prevent death and lung injury to marine turtles. However, the empirical and theoretical basis for this specific number is weak. Although additional experiments with turtles and underwater explosives are unlikely, some knowledge gained from marine mammal studies in recent years may be applicable. It is recommended that existing data be reviewed and modeling conducted to calculate mortality/injury ranges for marine turtles using standard sound level metrics and incorporating detonation characteristics appropriate for offshore structure removals. This would provide a firmer foundation for a turtle "safety range."

Marine Mammals

Only recently have experimental studies of explosive impacts on marine mammals been conducted, using animal carcasses. For many years, the only data available for predicting blast impacts on marine mammals were extrapolations from experiments on terrestrial mammals submerged in ponds and opportunistic post-mortem examinations of stranded animals following detonations.

There have been numerous attempts to model explosive impacts on marine mammals. Most of the research has focused on larger explosions associated with military testing such as ship shock trials. There also has been considerable research into sublethal auditory effects such as TTS and permanent threshold shift (PTS), as well as behavioral responses to underwater noise. Much of the behavioral research has focused on seismic surveys using airguns rather than explosives. Both blast injury and auditory effects are topics of ongoing investigations. Since existing marine mammal injury models are based on old and very limited data, it is likely that these models will be refined or new ones developed as more information becomes available.

For marine mammals as well as marine turtles, an important goal is calculating the likely extent of mortality and injury zones so that this area can be monitored for the presence of animals prior to detonations. Both the 1995 and 2002 regulations issued by the NMFS for incidental take of bottlenose and spotted dolphins in the Gulf of Mexico specified a "safety range" of 3,000 ft (914 m). This range for marine mammals is not based on any independent observations or modeling, but is simply the same range used for marine turtles under the "generic consultation" under Section 7 of the ESA.

Generic consultation experience (using the 3,000-ft [914-m] monitoring range) suggests that it has been effective in preventing most deaths or serious injuries of marine mammals. However, as noted previously for marine turtles, the basis for this specific number is weak, as it was not developed specifically for marine mammals. As additional data for blast injury in marine mammals become available and new or refined models are developed, it is recommended that mortality/injury zones be calculated for marine mammals using standard sound level metrics and incorporating detonation characteristics appropriate for offshore structure removals. This would provide a firmer foundation for a marine mammal "safety range."

Auditory effects such as TTS and PTS may occur beyond the "safety range" monitored during structure removals. These effects are of particular concern for marine mammals because of the regulatory implications of the MMPA, which prohibits "harassment." In various regulations for ship shock trial and seismic surveys, NOAA-Fisheries ([NOAA-F]; previously NMFS) has accepted TTS as a criterion for marine mammal harassment. This is an area of ongoing research in which criteria are being developed and refined. The MMS should coordinate with NOAA-F to make use of the most recent findings and criteria in evaluating auditory impacts on marine mammals.

Physics of Underwater Detonations

The understanding of the physical principles of underwater detonations and of the propagation of shock and sonic waves in the surrounding medium is in itself quite well developed. There are, however, significant gaps in the application of this knowledge to actual removal of offshore structures. The containment effect provided by setting the structure-cutting charges below a minimum prescribed depth of sediment has not been documented for a comprehensive range of seafloor consistencies, with the result that the extent of the transmission of explosive energy into the water column may be significantly greater than expected. Much of what is known from experience regarding underwater detonations within the seafloor comes from rock demolition blasting, which by its very nature is performed in an altogether different medium from the relatively compliant upper layers of sediment in which structure-cutting charges are deployed.

A systematic research effort should be undertaken to model numerically the blast propagation for a range of charge sizes consistent with structure removal practices through a wide variety of sediment types and for different deployment depths below the sediment surface. Such modeling should extend to the transfer of energy into the water column both from the shock wave propagating through the interface and later decaying into an acoustic signal, and from the oscillating bubble of detonation gases when breakout into the water does take place. Experimental validation of model results at every possible opportunity should form an integral part of the study; this requires accurate measurement of acoustic levels, and preferably full waveform recording, at one or more locations in the water columns as well as characterization of the sediment firmness near the structures being removed, which could be done by penetrometer probing or similar techniques.

Once a reliable modeling approach has been generated and validated, forecasting of the acoustic levels distribution for planned operations would become possible from the type and location of the charge to be exploded, the depth of the water column, and the measured properties of the sediment in which the detonation occurs. In combination with improved estimation of impact thresholds based on appropriate and standardized sound metrics for marine mammals and turtles, such a modeling-based assessment of each planned decommissioning operation involving explosive removal of underwater structures would provide the best ability to minimize its repercussions on marine life.

ES-6 Conclusions

A series of conclusions were reached following compilation, review, analysis, and summarization of data sources pertinent to the use of underwater explosives in platform removal, the presence of sensitive marine resources and impacts associated with underwater explosives use as applied to platform removal. Recognized data gaps and recommendations for future research also were identified.

The most commonly used technique for explosive cutting of piles and conductors is with bulk explosive charges. Other techniques such as ring charges, focusing charges, linear shaped charges, and cutting tape are used in some instances. Increased use of techniques that involve smaller charge sizes could reduce potential impacts on marine life.

The physical principles of underwater detonations and of the propagation of shock and sonic waves in the surrounding medium are well understood, but there are significant gaps in applying this knowledge to actual removal of offshore structures. It is recommended that a research effort be undertaken to model numerically blast propagation for a range of charge sizes consistent with structure removal practices through a variety of sediment types and for different deployment depths below the sediment surface. Experimental validation of model results should form an integral part of the study. Ultimately, forecasting of the acoustic levels distribution for planned operations would become possible from the type and location of the charge to be exploded, the depth of the water column, and the measured properties of the sediment in which the detonation occurs.

Environmental data concerning platform removals serve two main purposes: 1) to allow impacts to be estimated (e.g., numbers of animals that may be killed or injured during structure removals); and 2) to aid in developing or refining mitigation measures that prevent or reduce the likelihood of impacts. Impact estimation is the main goal with respect to marine fishes, whereas for marine turtles and marine mammals, mitigation is the main goal (i.e., predicting the areal extent of mortality and injury zones so that these can be monitored prior to detonation to prevent impacts).

There are important differences among marine fishes, marine turtles, and marine mammals with respect to the types and adequacy of data available. In general, marine fishes are the best-studied group, and marine turtles the least studied. Effects of underwater explosions on fishes have been studied and modeled extensively, and field studies have quantified fish kills associated with structure removals in the Gulf of Mexico. For marine turtles, there have been no laboratory studies of blast injury, only limited field observations and experiments, and no mechanistic models developed specifically to estimate impacts. For many years, the main data available for predicting both blast and auditory impacts on marine mammals were extrapolations from terrestrial mammal studies, but ongoing studies are underway that will aid in developing improved mortality, injury, and auditory impact criteria.

For predicting impacts on marine fishes, the empirical data from observations during actual structure removals would seem to be more useful than any attempt to calculate impacts based on experiments or mechanistic models. Since existing observations cover a limited geographic and water depth range, additional observations will be needed to better estimate future impacts.

Years of experience using the 3,000-ft (914-m) "safety range" monitored under the "generic consultation" suggest it has been effective in preventing most deaths and serious injuries of marine turtles and marine mammals. However, the empirical and theoretical basis for this specific number is weak. It is recommended that mortality/injury zones be calculated for marine turtles and marine mammals using standard sound level metrics and incorporating detonation characteristics appropriate for offshore structure removals. This would provide a firmer foundation for marine turtle and marine mammal "safety ranges."

In all three groups, there is relatively little information about sublethal impacts, particularly on the auditory system. While mitigation measures appear to be effective in preventing death or injury of mammals and turtles, it is uncertain to what extent sublethal effects may be occurring beyond the safety range. Recent and ongoing studies may provide the basis for estimating auditory impacts in marine mammals, which are particularly important in the regulatory context of "harassment" under the MMPA. There is almost no information to estimate auditory impacts on marine turtles.

The time interval between shots may be an important mitigation measure. The amount of time for an animal to recover from a shock wave is unknown. Do closely spaced shock waves, each of which is insufficient to cause damage, cause damage in a proportion to the sum of the damage parameters or a sum of a time dependent percentage of damage parameters? The effect of short time intervals between blasts such as those used in Gulf of Mexico structure removals has not been addressed.

The Office of Naval Research (ONR) is conducting research on physical and auditory effects of blast parameters on marine mammals and detection of marine mammals with passive acoustic devices. Synergy between MMS and the ONR in these areas of research would be fruitful. The Department of the Navy, Naval Surface Warfare Center is measuring actual blast parameters in the sea and working on new and/or revisions to blast propagation models. Synergy with this group would also be fruitful.

To date, mitigation and monitoring requirements for structure removals in the Gulf of Mexico have focused on marine turtles, bottlenose dolphins, and spotted dolphins. As structures are removed in greater water depths, many more species of marine mammals are likely to be encountered, including one endangered species (sperm whale) and other deep-diving species (such as beaked whales) that pose challenges for detection. Passive acoustic monitoring could aid in the detection of sperm whales. Not enough is known about the vocal behavior of beaked whales and some other species to determine the probability of their being detected by passive acoustic monitoring.

CHAPTER 2
INTRODUCTION

Nearly 4,000 oil and gas structures currently exist in Federal waters of the U.S. outer continental shelf (OCS), with the vast majority present in the Gulf of Mexico. The primary purpose of these structures (e.g., fixed platforms) is to develop and produce oil, natural gas, and gas condensates from offshore hydrocarbon reservoirs. Once offshore production from a producing field becomes uneconomic, the lease(s) may be terminated by the operator. As one of the conditions allowing the Federal government to lease offshore blocks to interested oil and gas operators, lease clearance requirements mandate that operators (responsible for installation and operation of a platform) subsequently remove the structure within a year of lease termination.

Platform removal typically involves the use of explosives to sever platform legs several feet below the seafloor. A typical fixed platform and its primary components are depicted in **Figure 2.1**. Historically, offshore development and production of oil and gas reserves has occurred in shelf waters. Consequently, most platform removals conducted to date have been located in shallower water depths (i.e., <200 m). Movement of production platforms farther offshore, coupled with recent interest in deepwater development, however, has raised the issue of future platform removal in deeper OCS waters (e.g., over the continental slope). Further, the presence of listed (i.e., endangered or threatened species listed or proposed for listing under the Endangered Species Act [ESA]) and/or protected species (i.e., marine mammals protected under the Marine Mammal Protection Act [MMPA]) in marine waters, coupled with the mandate to minimize or eliminate the potential for impact to these species, underscores the need to fully understand the environmental impacts associated with explosive platform removal.

To properly assess the impacts associated with explosive platform removal, the U.S. Department of the Interior, Minerals Management Service (MMS) requires access to the best available information. Topics of interest in this regard include a thorough characterization of explosive removal technologies and techniques, and the environmental impacts resulting from these underwater demolitions. The focus of the present study was to collect and synthesize existing information relevant to explosive removal of offshore structures in aquatic environments. While the expected application of this knowledge may include U.S. waters (e.g., Gulf of Mexico, California, Alaska OCS), the scope of this effort is worldwide. Sensitive marine resources considered in this analysis include marine fishes, marine turtles, and marine mammals.

2.1 MMS Mission and Regulations

The MMS is mandated by the OCS Lands Act, as amended, to manage the development of OCS oil, gas, and mineral resources, while protecting the human, marine, and coastal environments. While mineral resource exploration and development/ production on the OCS is typically represented by the use of mobile offshore drilling units or the placement of fixed or floating platforms, the final stages of facility

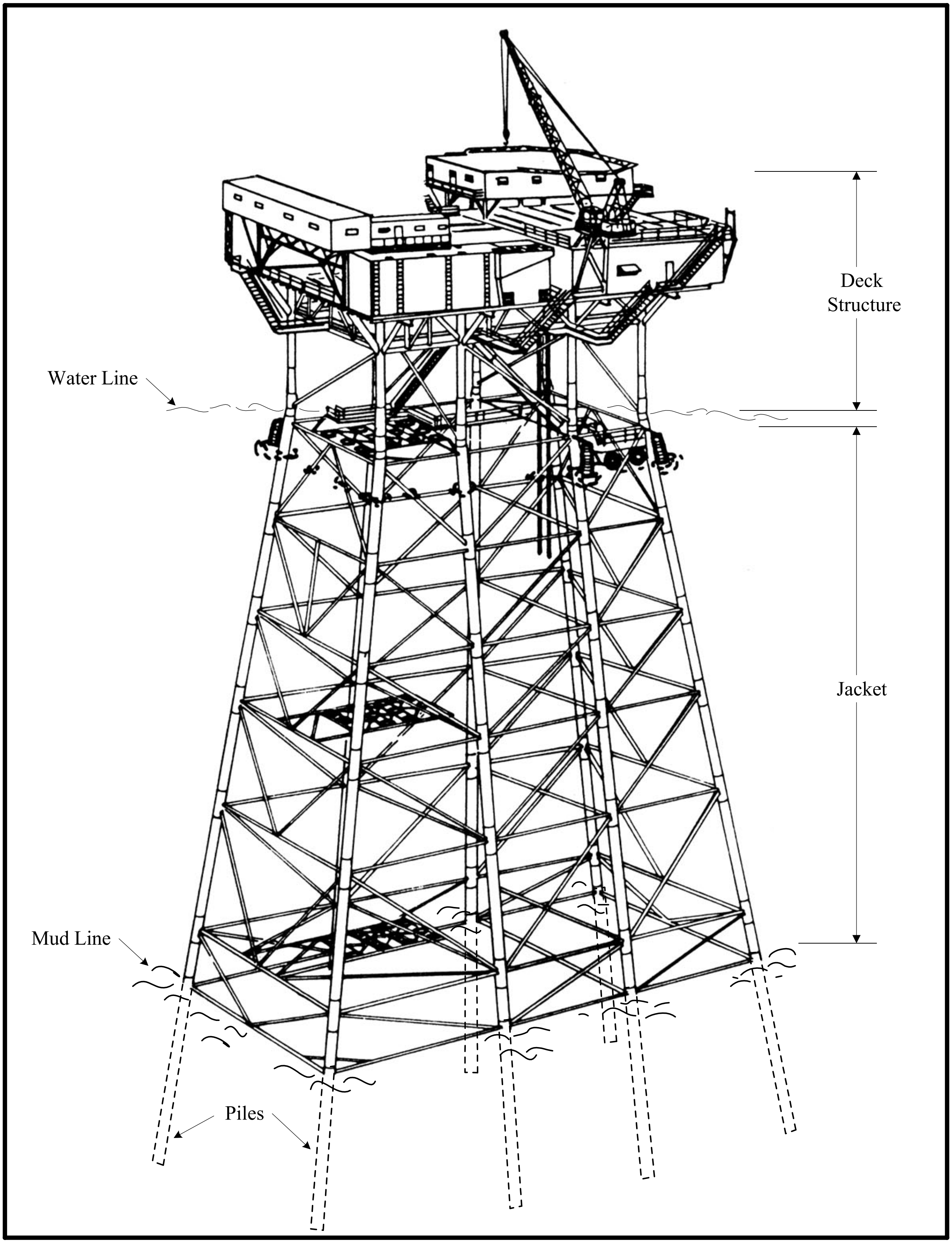

Figure 2.1. Profile diagram showing the major components of a representative fixed oil and gas platform.

decommissioning and lease abandonment frequently entail the removal of a platform that has been fixed to the seafloor.

Regulations relevant to OCS oil and gas operations are codified in 30 Code of Federal Regulations (CFR) Part 250. **Table 2.1** summarizes those portions of the Federal regulations that pertain to the decommissioning and removal of OCS oil and gas facilities through 1995.

The Marine Board of the National Research Council (NRC) (NRC, 1996) published an analysis of offshore structure removal techniques ("An Assessment of Techniques for Removing Offshore Structures") in early 1996. In April 1996, MMS convened the International Decommissioning Workshop in New Orleans, LA to discuss the recommendations in the NRC report and current industry decommissioning practices. On 8 August 1996, MMS published a notice (*Federal Register* 61:41,422) requesting comments on plans to further refine previous workshop recommendations. Several other public workshops also were held by MMS to solicit responses and recommendations regarding decommissioning operations.

In May 2002, MMS issued a final rule (*Federal Register* 67(96):35,397-35,412) amending its regulations governing oil and gas operations on the OCS to update decommissioning requirements. The rule included requirements for plugging a well, decommissioning a platform and pipeline, and clearing a lease site. MMS restructured and updated the requirements to make the regulations more user-friendly and to reflect changes in technology. Final technical changes implemented in July 2002 further ensure that lessees and pipeline right-of-way holders conduct their decommissioning operations safely and effectively. Specifically, 30 CFR 250 Subpart Q was implemented to 1) determine that decommissioning activities comply with regulatory requirements and approvals and to 2) ensure that site clearance and platform (or pipeline removal) are properly performed to protect marine life and the environment, and do not conflict with other users of the OCS. **Table 2.2** outlines the May 2002 major elements of the final rule that are relevant to platform removal, as found in Section 250.1725-250.1730 of the final rule. **Table 2.3** summarizes revised reporting requirements effective July 2002.

MMS also coordinates with the National Oceanic and Atmospheric Administration, Fisheries Division (NOAA-F; formerly the National Marine Fisheries Service [NMFS]) in compliance with existing environmental laws – ESA for listed species (i.e., all marine turtles, select marine mammals) and MMPA (protected marine mammals).[1]

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[1] For proposed activities that may affect the endangered West Indian manatee, MMS consults with the U.S. Fish and Wildlife Service in a similar role. Because manatees are strictly inland waterway/near coastal water inhabitants of the Gulf, it is extremely unlikely that they will be affected by explosive platform removals on the OCS.

Table 2.1

Summary of Minerals Management Service (MMS) Regulatory Requirements Relevant to the Decommissioning of Outer Continental Shelf (OCS) Oil and Gas Facilities, as Codified in 30 CFR Part 250 (Adapted from: MMS and California State Lands Commission 1997)

Regulation Title and Section	Relevant Requirements
Permanent Abandonment of Wells (250.110, 250.111, 250.112, 250.114)	• All well sites shall be cleared in a manner so as to avoid conflict with other uses of the OCS. • Lessee shall not initiate abandonment activities without the prior approval of the MMS District Supervisor. • Lessee must submit a request to abandon a well on Form MMS-124 (Sundry Notices and Reports on Wells) to the MMS District Supervisor for approval; subsequently, a report outlining abandonment procedures must be submitted to the MMS within 30 days of completion of the work. • Form MMS-124 shall specify the date the work is to be performed, the extent of the area to be searched around the location (e.g., well site), and the search methods used. • All wellheads, casings, pilings, and other obstructions shall be removed to a depth of at least 15 ft below the mud line, or to a depth approved by the MMS District Supervisor. • Lessee shall verify that the location has been cleared of all obstructions. • The requirements for removing subsea wellheads or obstructions, or for verifying location clearance, may be reduced or eliminated if the MMS District Supervisor determines that the wellheads or other obstructions do not constitute a hazard to other uses of the seafloor or other legitimate uses of the area. • Lessee shall verify site clearance after abandonment by one or more of the following methods, as approved by the MMS District Supervisor: 1) drag trawl in two directions across each location; 2) perform a diver search around the wellbore; 3) scan across the location with a side-scan or on-bottom scanning sonar; or 4) use other methods based on particular site conditions. • Lessee shall submit certification that the area was cleared of all obstructions, the date the work was conducted, the extent of the area searched around the location (e.g., well site), and the search methods utilized; lessee to use Form MMS-124.

Table 2.1. Summary of Minerals Management Service (MMS) Regulatory Requirements Relevant to the Decommissioning of Outer Continental Shelf (OCS) Oil and Gas Facilities, as Codified in 30 CFR Part 250 (Adapted from: MMS and California State Lands Commission 1997) (continued).

Regulation Title and Section	Relevant Requirements
Temporary Abandonment of Wells (250.113)	• Subsea wellheads, casing stubs, or other obstructions remaining after temporary abandonment above the seafloor shall be protected in such a manner as to allow commercial fisheries gear to pass over the structure without damage to the structure or the fishing gear. • Depending upon water depth, the nature and height of the obstruction above the seafloor, and the types and periods of fishing activity in the area, the MMS District Supervisor may waive this requirement. • Lessee shall follow appropriate U.S. Coast Guard requirements in identifying and reporting subsea wellheads, casing stubs, and other obstructions extending above the mud line.
Platform Removal and Location Clearance (250.143)	• Structures are to be removed in a manner approved by the MMS Regional Supervisor that ensures that the location has been cleared of all obstructions to other activities in the area. • All platforms (including casing, wellhead equipment, templates, and pilings) shall be removed to a depth of a least 15 ft below the ocean floor, or to a depth approved by the MMS Regional Supervisor based upon the type of structure or ocean bottom conditions. • Lessee shall verify that the location has been cleared of all obstructions. • Results of a site-specific clearance survey shall be submitted to the MMS Regional Supervisor. • A letter certifying that the area was cleared of all obstructions, the date the work was performed, the extent of the area surveyed, and the survey methods used shall be submitted to the MMS Regional Supervisor.
Abandonment of Pipelines (250.156)	• A pipeline may be abandoned in place, if the MMS Regional Supervisor determines that it does not constitute a hazard to navigation, commercial fishing operations, or unduly interfere with other OCS uses. • Pipelines abandoned in place shall be flushed, filled with seawater, cut, and plugged; pipeline ends must be buried at least 3 ft.

Table 2.2

Summary of Pertinent Requirements for Platform and Other Facility Removal from the Outer Continental Shelf (OCS), Per Updated Regulations (Adapted from: *Federal Register* 67(96):35,397-35,412)

30 CFR Section	Title and Summary of Requirement(s)
250.1725	When do I have to remove platforms and other facilities? An operator: (a) Must remove all platforms and other facilities within 1 year after the lease or pipeline right-of-way terminates, unless receiving approval to maintain the structure to conduct other activities. Platforms include production platforms, well conductors, single-well caissons, and pipeline accessory platforms. (b) Before removing a platform or other facility, must submit a final removal application to the Regional Supervisor for approval and include the information listed in Sec. 250.1727. (c) Must remove a platform or other facility according to the approved application. (d) Must flush all production risers with seawater before removal, (e) Must notify the Regional Supervisor at least 48 hours before beginning the removal operations.
250.1726	When must I submit an initial platform removal application, and what must it include? An initial platform removal application is required only for leases in the Pacific OCS Region or the Alaska OCS Region. It must include the following information: (a) Platform or other facility removal procedures, including the types of vessels and equipment to be used; (b) Facilities (including pipelines) to be removed or left in place; (c) Platform or other facility transportation and disposal plans; (d) Plans to protect marine life and the environment during decommissioning operations, including a brief assessment of the environmental impacts of the operations, and procedures and mitigation measures to be taken take to minimize the impacts; and (e) A projected decommissioning schedule.
250.1727	What information must I include in my final application to remove a platform or other facility? Operators must submit a final application to remove a platform or other facility to the Regional Supervisor for approval. This requirement applies to leases in all MMS Regions. If proposing use of explosives, operators are to provide three copies of the application. If no explosives are proposed, only two copies of the application are to be provided. The following information is to be included in the final removal application, as applicable:

Table 2.2. Summary of Pertinent Requirements for Platform and Other Facility Removal from the Outer Continental Shelf (OCS), Per Updated Regulations (Adapted from: *Federal Register* 67(96):35,397-35,412) (continued).

30 CFR Section	Title and Summary of Requirement(s)
	(a) Identification of the applicant including: (1) Lease operator/pipeline right-of-way holder; (2) Address; (3) Contact person and telephone number; and (4) Shore base. (b) Identification of the structure being removed including: (1) Platform Name/MMS Complex ID Number; (2) Location (lease/right-of-way, area, block, and block coordinates); (3) Date installed (year); (4) Proposed date of removal (month/year); and (5) Water depth. (c) Description of the structure being removed including: (1) Configuration (attach a photograph or a diagram); (2) Size; (3) Number of legs/casings/pilings; (4) Diameter and wall thickness of legs/casings/pilings; (5) Whether piles are grouted inside or outside; (6) Brief description of soil composition and condition; (7) The sizes and weights of the conductor, topsides (by module), conductors, and pilings; and (8) The maximum removal lift weight and estimated number of main lifts to remove the structure. (d) A description, including anchor pattern, of the vessel(s) to be used to remove the structure. (e) Identification of the purpose, including: (1) Lease expiration/right-of-way relinquishment date; and (2) Reason for removing the structure. (f) A description of the removal method, including: (1) A brief description of the method to be used; (2) If explosives are to be used, the following: (i) Type of explosives; (ii) Number and sizes of charges;

Table 2.2. Summary of Pertinent Requirements for Platform and Other Facility Removal from the Outer Continental Shelf (OCS), Per Updated Regulations (Adapted from: *Federal Register* 67(96):35,397-35,412) (continued).

30 CFR Section	Title and Summary of Requirement(s)
	(iii) Whether single shot or multiple shots are to be employed; (iv) If multiple shots, the sequence and timing of detonations; (v) Whether bulk or shaped charges are to be used; (vi) Depth of detonation below the mud line; and (vii) Whether explosives are being placed inside or outside of the pilings; (3) If divers or acoustic devices are to be used to conduct a pre-removal survey to detect the presence of turtles and marine mammals, a description of the proposed detection method; and (4) A statement whether or not the operator will use transducers to measure the pressure and impulse of the detonations. (g) Operator plans for transportation and disposal (including as an artificial reef) or salvage of the removed platform. (h) If available, the results of any recent biological surveys conducted in the vicinity of the structure and recent observations of turtles or marine mammals at the structure site. (i) Operator plans to protect archaeological and sensitive biological features during removal operations, including a brief assessment of the environmental impacts of the removal operations and procedures and mitigation measures to be taken to minimize such impacts. (j) A statement whether or not the operator will use divers to survey the area after removal to determine any effects on marine life.
250.1728	To what depth must I remove a platform or other facility? (a) Unless the Regional Supervisor approves an alternate depth under paragraph (b) of this section, operators must remove all platforms and other facilities (including templates and pilings) to at least 15 ft below the mud line. (b) The Regional Supervisor may approve an alternate removal depth if: (1) The remaining structure would not become an obstruction to other users of the seafloor or area, and geotechnical and other information you provide demonstrates that erosional processes capable of exposing the obstructions are not expected; or (2) The operator determines, and MMS concurs, that divers must be used and the seafloor sediment stability poses safety concerns; or (3) The water depth is greater than 800 m (2,624 ft).

Table 2.2. Summary of Pertinent Requirements for Platform and Other Facility Removal from the Outer Continental Shelf (OCS), Per Updated Regulations (Adapted from: *Federal Register* 67(96):35,397-35,412) (continued).

30 CFR Section	Title and Summary of Requirement(s)
250.1729	After I remove a platform or other facility, what information must I submit? Within 30 days after an operator removes a platform or other facility, the operator must submit a written report to the Regional Supervisor that includes the following: (a) A summary of the removal operation including the date it was completed; (b) A description of any mitigation measures taken; and (c) A statement signed by the operator's authorized representative that certifies that the types and amount of explosives used in removing the platform or other facility were consistent with those set forth in the approved removal application.
250.1730	When might MMS approve partial structure removal or toppling in place? The Regional Supervisor may grant a departure from the requirement to remove a platform or other facility by approving partial structure removal or toppling in place for conversion to an artificial reef or other use if the following conditions are met: (a) The structure becomes part of a State artificial reef program, and the responsible State agency acquires a permit from the U.S. Army Corps of Engineers and accepts title and liability for the structure; and (b) The operator satisfies any U.S. Coast Guard (USCG) navigational requirements for the structure.

Table 2.3

Summary of Reporting Requirements, Per Updated Decommissioning Regulations
(From: *Federal Register* 67(96):35,397-35,412)

Citation (30 CFR 250 subpart Q)	Reporting Requirement
1703; 1704….	Request approval for decommissioning.
1704(f); 1712; 1716; 1717; 1721(a), (f), (g); 1722(a),(b), (d); 1723(b); 1743(a)	Submit form MMS-124 to plug wells; provide subsequent report; request alternate depth departure; request procedure to protect obstructions above seafloor; report results of trawling; certify area cleared of obstructions; remove casing stub or mud line suspension equipment and subsea protective covering; or other departures.
1713 (Final New)...........	Notify MMS 48 hours before beginning operations to permanently plug a well.
1721(e); 1722(e), (h)(1); 1741(c).	Identify and report subsea wellheads, casing stubs, or other obstructions; mark wells protected by a dome; mark location to be cleared as navigation hazard.
1722(c), (g)(2) (Final New)...	Notify MMS within 5 days if trawl does not pass over protective device or causes damages to it; or if inspection reveals casing stub or mud line suspension is no longer protected.
1722(f), (g)(3)...............	Submit annual report (75 copies) on plans for re-entry to complete or permanently abandon the well and inspection report.
1722(h) (Final New)...........	Request waiver of trawling test.
1704(a); 1726 (Proposed New)…	Submit initial decommissioning application in Pacific OCS and Alaska OCS Regions.
1704(b); 1725; 1727; 1728; 1730.	Submit final application to remove platform or other subsea facility structures (including alternate depth departure) or approval to maintain, to conduct other operations, or to convert to artificial reef.
1725(e) (Final New).........	Notify MMS 48 hours before beginning removal of platform and other facilities.
1704(c); 1729 (Final New)……..	Submit post platform or other facility removal report.
1740(b)(5), (c)(3); 1740(g)(1); 1743(b)	Request approval of well site, platform, or other facility clearance method; including contacting pipeline owner or operator.
1743(b).......................	Verify permanently plugged well, platform, or other facility removal site cleared of obstructions and submit certification letter.
1704(d); 1751; 1752...........	Submit application to decommission pipeline in place or remove pipeline.
1753 (Final New).............	Submit post-pipeline decommissioning report.
1700 through 1754...........	General departure and alternative compliance requests not specifically covered elsewhere in subpart Q regulations.

2.1.1 ESA Consultation and Related Requirements

MMS complies with the Section 7 provisions of the ESA through consultation to minimize potential impacts to listed species. All sea turtle species occurring in offshore waters of the Gulf of Mexico are protected under the ESA.

In 1988, the NMFS issued a "generic consultation" covering structure removal activities on the Gulf of Mexico continental shelf (NMFS 1988), following completion of an MMS programmatic environmental assessment that evaluated structure removal activities (MMS 1987). The generic consultation specified mitigation and monitoring requirements to prevent death or injury of sea turtles.

In order for a platform removal proposal using explosive technology to be considered under the generic consultation, it must conform to the following specifications:

1) Each explosive charge must be 50 lb or less;
2) Detonations must be limited to groups of eight or less with a minimum of 0.9 sec between detonations;
3) High velocity explosives must be used with a detonation rate of 7,600 m/sec or greater; and
4) Charges must be placed a minimum of 5 m (15 ft) below the mud line.

The NOAA-F requires the following mitigation measures under the generic consultation:

1) Qualified observers must monitor the area around the site prior to, during, and after detonation of charges. This observer coverage must begin 48 hours prior to the detonation of charges, and if sea turtles are thought to be resident in the area, pre- and post-detonation diver surveys must be performed;
2) A 30-minute aerial survey must be performed within 1 hour before and 1 hour after each blasting sequence;
3) If sea turtles or marine mammals are observed within 914 m (1,000 yd) of the structure, detonation will be delayed until such creatures are beyond the 914 m (1,000 yd) range, and the aerial survey repeated;
4) Detonation of explosives will occur no sooner than 1 hour after sunrise and no later than 1 hour prior to sunset;
5) During all diving operations, divers must look for sea turtles and marine mammals. All sightings must be reported; and
6) Use of "scare charges" or explosive devices to frighten marine mammals out of the blasting area is discouraged, and may be used only after obtaining special permission.

Several listed marine mammal species may occur in the Gulf of Mexico (see **Section 5.3**), the most common of which is the endangered sperm whale, a species that prefers the deeper waters (>200 m) of the Gulf. All endangered or threatened marine mammals are unlikely to be affected by platform removals on the Gulf of Mexico continental shelf because no listed species are commonly found there. Therefore, no marine mammals are included in the ESA "generic consultation" (NMFS 1988). Future structure removals in deepwater, however, may affect the endangered sperm whale and would require additional consultation between MMS and NOAA-F under Section 7 of the ESA. The MMS is preparing a biological assessment for the ESA consultation to address the explosive removal of oil and gas structures at all water depths. The threatened and endangered species expected to be addressed during the ESA consultation will be sea turtles and the sperm whale.

MMS has also implemented region-specific restrictions on explosive platform removal activities. For example, the Gulf of Mexico OCS Region has implemented Notice to Lessees and Operators (NTL) No. 2001-G08. This NTL places restrictions on explosive platform removals, requiring operators to monitor for the presence of sea turtles or marine mammals and to conduct explosive operations in a manner that will minimize the likelihood of harm to these individuals. Further, NTL 2001-G08 also requires that the MMS must initiate a new ESA Section 7 consultation with the NMFS for the following types of explosive structure removal method applications:

1) An application proposing an explosive structure removal operation that does not comply with the criteria and terms and conditions of the ESA Section 7 "generic consultation" noted above; and
2) An application proposing an explosive removal operation in water depths 200 m (656 ft) or greater. The Gulf of Mexico OCS Region has determined that explosive removals in these areas "may affect" sperm whales, an endangered species.

2.1.2 MMPA Concerns

Killing or injuring any marine mammal is considered to be "take" and is prohibited under the MMPA. The unintentional taking of a protected marine mammal, termed incidental take, may be approved by NOAA-F if such take is determined to produce only a negligible impact to a species stock or habitat. In practice, MMPA-related efforts have focused on bottlenose dolphins and spotted dolphins, which are by far the most common marine mammals on the Gulf of Mexico continental shelf.

In 1995, NMFS established appropriate structure removal criteria (i.e., maximum charge size, monitoring and reporting requirements) for waters of the Gulf of Mexico (*Federal Register* 60(197):53,139-53,147). These criteria took into account the potential for the incidental take of several protected marine mammal species, specifically outlining regulations authorizing and governing the taking of bottlenose and spotted dolphins incidental to the removal of oil and gas drilling and production structures in state and OCS waters of the Gulf. The incidental taking of small numbers of marine mammals may be authorized under the MMPA if certain findings are made and regulations are issued that include requirements for monitoring and reporting. As noted by NMFS, these regulations authorized the unintentional incidental take of marine mammals in connection with such activities over a 5-year period (1995-2000) and prescribed methods of taking and other means of effecting the least practicable adverse impact on the species and its habitat. On 13 November 2000, these regulations expired and NMFS could no longer issue authorization (i.e., Letters of Authorization [LOAs]) for structure removal activities in the Gulf of Mexico.

At the request of the oil and gas industry, NMFS established new criteria in 2002 relevant to structure removal in the Gulf of Mexico. The 2002 criteria were established as an interim policy statement (*Federal Register* 67(148):49,869-49,875) to provide the industry with protection from incidental take liability under the MMPA, given that the 1995 requirements had expired. The current criteria are effective only for the period 1 August 2002 through 2 February 2004.

The incidental take regulations issued by NMFS in 1995 and 2002 cover only bottlenose and spotted dolphins. These regulations, which include mitigation and monitoring requirements, will expire in February 2004. The MMS has committed to petition NOAA-F for new regulations and incidental take authorization as part of their approval process to allow future removal of offshore structures in the Gulf of Mexico. For all dismantling operations requiring the use of explosives that do not meet the existing requirements, NOAA-F requires that applications for approval must be initiated on a case-by-case basis.

2.2 Study Purpose and Objectives

The purpose of the investigation was to collect and synthesize information on explosive removals of offshore structures in aquatic environments. This information is needed by MMS to assist in their review, monitoring, and evaluation of impacts associated with explosive platform removal.

The primary study objectives were to:

1) provide a summary of available information by topic;
2) identify information and data gaps that could be filled by subsequent research activities; and
3) recommend areas of research to meet MMS information needs.

Deliverables prepared under this contract include a unified electronic bibliography (a hard copy version is included with this report as the **Appendix**), a list of data and other sources, and this synthesis report summarizing the scope, coverage, and quality of the materials found.

2.3 Project Team

To address the study objectives, specialized technical expertise was incorporated into the project team, with several key individuals designated as Principal Investigators (PIs). A listing of key project personnel and their respective area(s) of expertise and affiliations follows:

- Continental Shelf Associates, Inc. (CSA) (Jupiter, FL) – prime contractor
    - Stephen T. Viada – Program Manager; PI, Marine Turtles
    - David B. Snyder – PI, Marine Fishes
    - M. John Thompson – PI, Platform Removal Techniques
    - Neal W. Phillips – Environmental Impacts of Explosives
    - Brian J. Balcom – Editor

- LGL Ltd. (King City, Ontario, Canada) – subcontractor
    - Denis Thomson – PI, Marine Mammals
    - W. John Richardson – Marine Mammals

- JASCO Research Ltd. (Victoria, British Columbia, Canada) – subcontractor
    - Roberto Racca – PI, Underwater Explosives and Platform Removal
    - David Hannay – Underwater Explosives and Platform Removal

Technical review regarding underwater explosives was also provided by William Poe of Explosive Service International, Ltd., Baton Rouge, LA. A Quality Review Board (QRB) also was formed to provide expert review and comment on the draft version of the information synthesis report. The QRB consisted of Charles Greene (Greeneridge Sciences, Santa Barbara, CA) and Greg Gitschlag (NMFS, Galveston, TX).

2.4 Study Methods and Report Organization

The study effort was divided into two separate tasks, as detailed below. Recognizing that the primary purpose of the study effort was to identify and review salient data sources for each topic area, pertinent references were used to 1) develop the Information Synthesis Report and 2) create a separate electronic database.

2.4.1 Task 1 – Information Search/Collection and Data Management

The PIs were used as resources to identify and judge the completeness of the database in each subject area. The goal of the information collection plan was to supply published and unpublished literature to each PI according to their individual needs and to compile a computerized bibliographic database. Information gathered included pertinent data sources in the following topics:

- Explosive Removal Methods;
- Physics of Underwater Explosions;
- Biological Resources;
- Impacts to Biological Resources; and
- Mitigation and Monitoring of Effects

For each reference incorporated into the bibliographic database, the following information was provided:

- Author;
- Date;
- Article or Chapter Title;
- Journal/book/volume information or location, if unpublished;
- Pages;
- Publisher;
- Geographic location covered, such as ecosystem, habitat, latitude/longitude;
- Key words and discipline; and
- Format/media (e.g., paper, magnetic disks or tapes), if data.

Unpublished data and ongoing research studies have been included as references in the database. The format for these references within the database includes the following:

- Data type;
- Data source and/or location;
- Collection location;
- Sampling period;
- Sampling frequency;
- Number of stations;
- Data availability (proprietary or non-proprietary);
- Key words;
- Accession number;
- Collector or research/institution; and
- Format/media (e.g., paper, magnetic disks or tapes), if data.

The information collection process represented a compilation of existing data from the CSA in-house database and library, from personal libraries of each PI, and from computer searches of online databases. The following journals were reviewed and organizations contacted:

- Acoustical Society of America;
- Journal of Geophysical Research;
- Geophysics;
- Journal of Computational Acoustics;
- NMFS; and
- Canadian Acoustical Association.

All data sources were organized within a preliminary electronic bibliographic database.

A large fraction of the literature dealing with sound and blast energy from underwater explosive detonations is not available in open publication. One of the project's subcontractors (JASCO) has participated in numerous studies that have resulted in reports and publications that would normally be difficult to obtain. JASCO maintains a large internal library of publications related to underwater blasts and underwater acoustics in general, including reports produced for or by the following members of government agencies, academia, and the private sector:

- U.S. Army Corps of Engineers;
- National Defence Headquarters Canada;
- Defence Research Establishment Pacific Canada;
- Defence Research Establishment Atlantic Canada;
- Naval Surface Warfare Center (San Diego, CA);
- Institute of Ocean Science (British Columbia, Canada); and
- Private petroleum companies.

JASCO also requested literature from a series of associates in government laboratories and universities with expertise in the fields of underwater acoustics, marine geophysics, and blast physics.

LGL Ltd. has an extensive library with relevance to impacts of underwater explosions on marine life. Most of the material is in the form of reports and gray literature, with only limited amounts of material in the published literature. Sources included the following:

- Reports produced by the Naval Surface Weapons Center, Dahlgren, Silver Spring, Cardrock, and Indian Head and the Lovelace Foundation (Albuquerque, NM). These include the results of experiments on terrestrial mammals and modeling done for various ship shock trials and other underwater explosions done by the U.S. Navy;
- Reports and guidelines for the use of explosives, including jetted charges by Fisheries and Oceans Canada;
- Regulations pertaining to underwater explosions published in the CFR; and
- Reports produced by the U.S. Army Corps of Engineers.

Online databases were searched using the DIALOG Information Retrieval Service. These database searches, conducted by Harbor Branch Oceanographic Institution, were completed for each specific topic area – explosive removal methods, physics of underwater explosions, biological resources, and impacts to biological resources. Databases searched included the following:

- Aquatic Science and Fisheries Abstracts;
- BIOSIS Previews (Biological Abstracts);
- CA Search (Chemical Abstracts);
- CENDATA;
- Conference Papers Index;
- Dissertation Abstracts;
- Energy Science and Technology;
- GEOREF (American Geological Institute);
- Life Sciences Collection;
- Meteorological and Geoastrophysical Abstracts;

- National Technical Information Service (NTIS);
- Oceanic Abstracts;
- Scisearch Database (Science Citation Index); and
- Zoological Record.

These data were incorporated into the preliminary bibliography database in an electronic and searchable format.[2] The preliminary bibliography was reviewed for completeness by the PIs. Additional citations and abstracts were identified and incorporated into the bibliography. In addition, supplemental information sources were identified through contacts with various agencies, organizations, and individuals. This revised bibliographic database was used in completion of the second task – the preparation of the Information Synthesis Report.

2.4.2 Task 2 - Information Synthesis Report

This Information Synthesis Report comprises nine separate and inter-related chapters. Chapter 1 (Executive Summary) provides an overview of the synthesis report – major findings, identified data gaps, and recommendations for future research – dealing with the explosive removal of offshore platforms and their effects on sensitive resources. Chapter 2 (Introduction) outlines the major objectives of the study effort, identifies the project team, outlines MMS mandate and regulatory requirements associated with OCS structure removal, summarizes the tasks completed, and outlines the organization of the synthesis report. Chapter 3 (Decommissioning and Explosive Removal Methods) provides a description of explosive structure removal methods, including methods that are presently in service and methods currently under design. Chapter 4 (Physics of Underwater Explosions) provides a detailed and technical description of the physics of underwater explosions, including shock wave and acoustic properties of explosive removals, and parameters that affect shock wave propagation and intensity. Chapter 5 (Affected Environment) provides individual summaries of marine fishes, marine turtles, and marine mammals, describing an overview of these biological resources. Chapter 6 (Environmental Consequences) provides a synthesis of environmental effects to each of the sensitive resources from explosive structure removals, based upon available literature and data. Chapter 7 (Mitigation and Monitoring) discusses mitigation and monitoring methods presently in use and proposed methods. Chapter 8 (Discussion and Recommendations) outlines a proposed impact matrix (i.e., threshold distances from an explosive source that, based on an analysis of available data, correspond to lethal, sublethal physiological, and sublethal behavioral impacts to marine fishes, marine turtles, and marine mammals), identifies alternative actions, summarizes identified data gaps, and provides summary recommendations for future research to address MMS needs. Chapter 9 provides a conclusion to the synthesis report.

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[2] i.e., ProCite. ProCite incorporates results from tagged DIALOG searches directly into a bibliographic database. For the final report, the ProCite bibliographic database was exported into Microsoft Access 2000. The Microsoft Access 2000 database is provided as the **Appendix** to this report.

CHAPTER 3
DECOMMISSIONING AND EXPLOSIVE REMOVAL METHODS

3.1 Background

To remove a fixed platform, the installation steps are essentially reversed. Topside equipment such as living quarters, generators, and processing equipment is taken off by crane and returned to shore for scrap or to be reused (see **Figure 2.1**). The deck sections are then lifted from the platform and placed on cargo barges for transportation to their disposal site. Conductors, flare piles, submerged wells, and caissons also are structures subject to explosive removal (see **Chapter 6**). MMS regulations require that the piles and well conductors be severed at least 5 m (15 ft) below the mud line and removed. Once the piles and conductors are disconnected from the seabed, they are lifted out and placed on a cargo barge for ultimate disposal.

Pilings and conductors can be cut by a number of mechanical means, including

- use of tungsten-carbide blade cutters contained in routine rig workover equipment;
- use of diamond wire and hydraulic shear cutters deployed by remotely operated vehicles (ROVs); and
- manually by divers through the use of mechanical or abrasive cutting techniques.

The safest and easiest cutting procedure is to place an explosive charge inside the piling at the desired depth and sever the piling explosively.

Underwater cutting of piles and conductors is a slow and hazardous process requiring extensive dive time and considerable risk to divers. Mechanical cutting also is not as reliable as explosive cutting, and the risk of failure is considerably higher than that associated with explosive techniques (Kaiser et al. 2002).

An Environmental Assessment (EA), prepared pursuant to National Environmental Policy Act (NEPA) of 1969 (42 U.S.C. 4321-4347) guidelines, as amended, is conducted for each platform removal application received by the MMS. In 1987, a programmatic EA was prepared by the MMS to assess the entire spectrum of potential environmental impacts associated with platform removal (MMS 1987). A site-specific EA is prepared for each individual platform removal proposal, with tiering off of the programmatic EA and containing site-specific environmental details from the specific site, and operational procedures for a specific platform removal effort (Richardson 1989). MMS is presently preparing an updated programmatic EA to consider explosive removal operations in all water depths. If explosives are used to cut the pilings and conductors during platform removal, there is the potential that sea turtles or other endangered or protected species (i.e., marine mammals) in the area could be harmed, as detailed previously in **Chapter 2**.

3.2 Presently Employed Explosive Cutting Techniques

3.2.1 Bulk Explosive Charges

The most commonly used technique for explosive cutting of piles and conductors is with bulk explosives such as C-4 or Comp B (**Figure 3.1**). These explosives are castable and moldable, have a high velocity on detonation, and a high shattering power. They are not as dangerous to handle as some other types of high explosives, and they can be molded in the field to specifically required sizes and shapes. This moldability characteristic is an important advantage explosive techniques have over conventional cutting techniques. During platform construction, piles are welded together with steel guides, called "stabbing guides," on the inside bottom of each pile section to facilitate mating with the next section. This reduces the inside diameter of the pile both above and below the weld. These inside pile diameter reductions are critical when using conventional cutting techniques where equipment must be lowered down the pile and then retrieved after the cut is made. When using bulk explosives, these variations in pile diameter are a relatively minor inconvenience. Bulk charges can be sized to sever a pile in the field and do not have to be retrieved. Bulk charges also can be re-shaped in the field when discrepancies between the "planned" and the "as built" diameters of piles or well strings are encountered. This flexibility is important because it allows jobs to proceed with relatively little delay.

Bulk charges are lowered into prepared pilings or well conductors and detonated nearly simultaneously with a 0.9-sec delay in groups of eight or less (**Figure 3.2**). After an eight charge detonation sequence, there is a pause. While there is no legal or permit-associated required length for this pause, contractors will usually pause 2 to 3 minutes before the next detonation sequence is initiated (W. Poe 2003, pers. comm.). On a normal platform, all piles and wells can be severed within an hour or two, including the time required for loading the charges and conducting the NOAA-F required aerial surveys for sea turtles and marine mammals.

Bulk explosives have a 95% success rate when sized properly. Increased water depth has no adverse impact on the success rate of bulk explosive cuts. If a bulk explosive does not sever a piling or well string on the first detonation, a back-up charge can be sized and deployed quickly. After more than a quarter century of use and hundreds of thousands of worker-hours, no serious injuries have been reported for handling or using bulk explosives in platform removal (NRC 1996).

3.2.2 Configured Bulk Charges

Configured bulk charges such as "ring charges" and "focusing" charges are designed to collide or "focus" the detonation front to concentrate more energy along the fracture line, and thus reduce the size of the charge needed to cut a piling. These types of charges have been effective in reducing "belling" or bulging out of the severed piling.

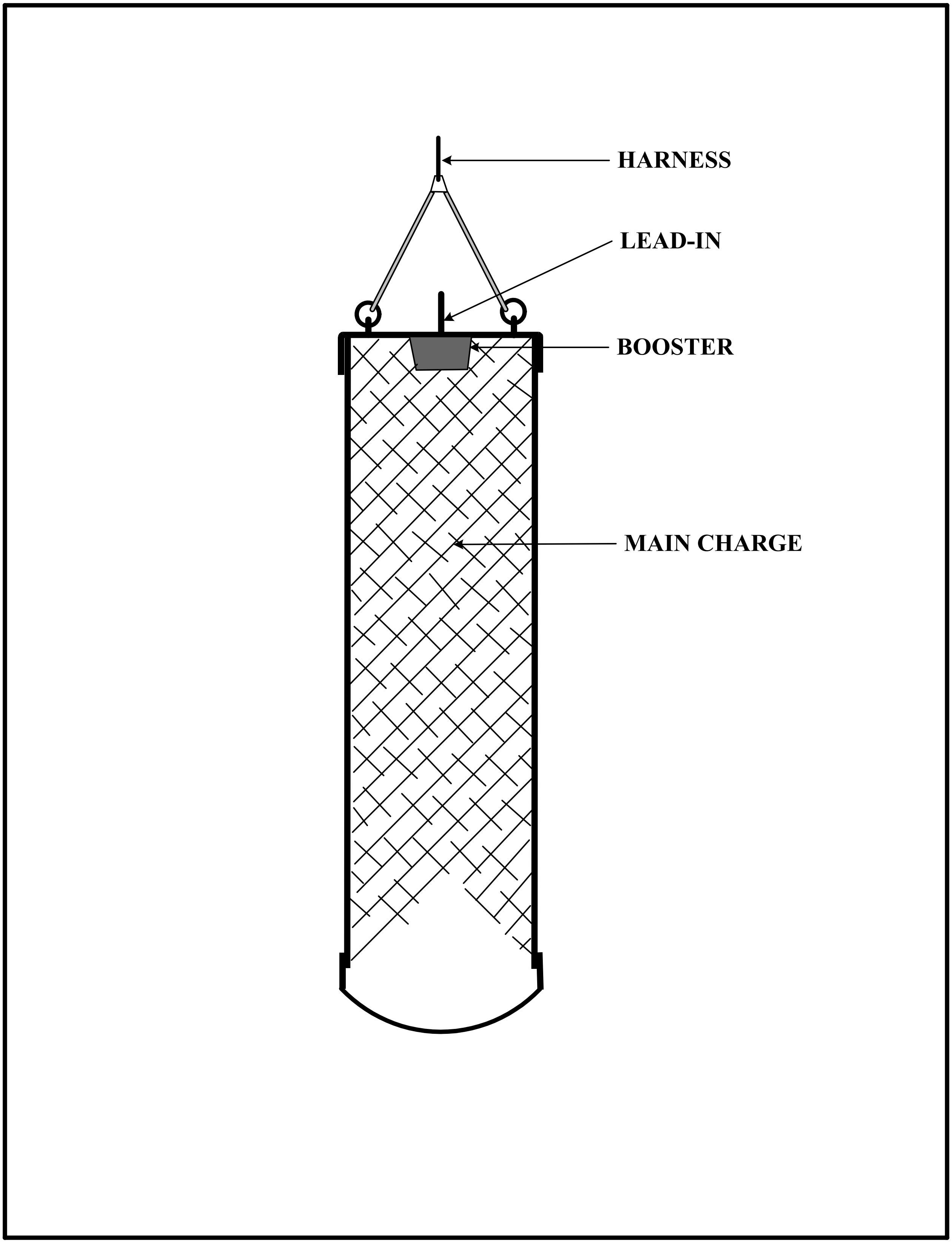

Figure 3.1. Bulk explosive charge (From: DEMEX 2002).

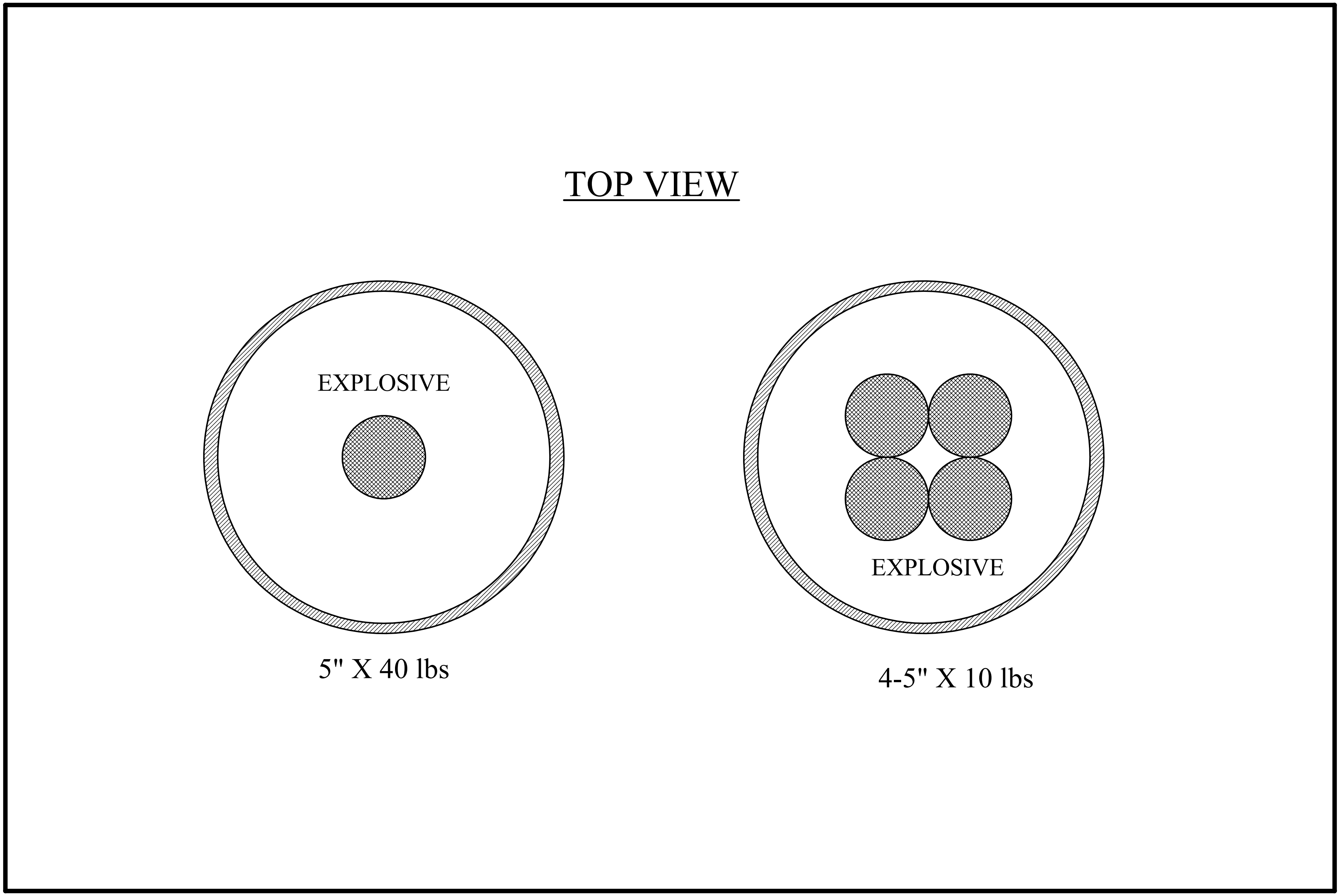

Figure 3.2. Bulk charge arrangement for larger diameters (From: DEMEX 2002).

Ring Charges

Ring charges (**Figure 3.3**) are made from the same material as bulk charges, primarily C-4 or Comp B formed into doughnut-shaped rings, which are lowered into the piling. These rings concentrate the explosive closer to the inside of the piling's walls, making it more effective. Ring charges can reduce the total weight of charges required to sever a specific piling by approximately 10% to 15% (NRC 1996).

Focusing Charges

Focusing charges (**Figure 3.4**) consist of explosives sandwiched between two "tamping" plates, one above and one below. These tamping plates have the effect of delivering more of the explosive's power horizontally to the piling walls and thus allowing the use of smaller charges. Reductions in explosive weight with focusing plates are comparable to reductions in weights associated with ring charges.

The drawback with both ring and focusing charge arrangements is that both must be prefabricated and sized to fit each application. Generally, there is some size variation built into each configuration, which will allow for minor variations of inside pile diameters or obstructions. Configured charges cannot be used to sever wells because the diameter of the inner casing is too small to accommodate the charge (NRC 1996).

3.2.3 Cutting Charges

Cutting charges include linear-shaped charges and "cutting tape." Each of these is discussed in greater detail below.

Linear-Shaped Charges

Linear-shaped charges use high-velocity explosive energy to accelerate a v-shaped band of cutting material, usually copper, in a high velocity jet that penetrates through the steel of the piling. Linear-shaped charges can be used in specifically manufactured containers that fit around the outside of the piling to cut pilings from the outside (**Figure 3.5**). Linear-shaped charges can also be positioned on the inside of platform legs using a running tool or articulated device for positioning the charge (**Figure 3.6**).

The performance of linear-shaped charges depends on the presence of an air space between the charge and the target. This required "stand-off" distance is a function of the thickness of the material to be cut. When accurately positioned to a precisely calculated stand-off distance between charge and target, linear-shaped charges yield very smooth cuts (NRC 1996).

Linear-shaped charges require long lead times to fabricate and accurate engineering data on the piling or caisson to be cut. If the thickness of a pile section is unknown (not unusual in older oil field structures), or if the pile is out of round,

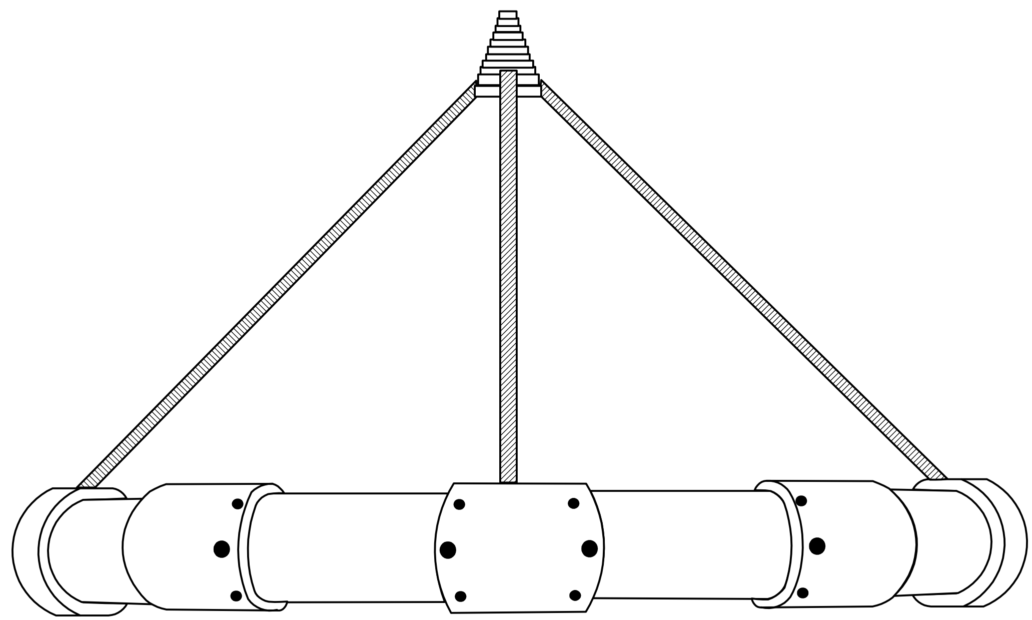

Figure 3.3. Configured bulk "ring charge" (From: DEMEX 2002).

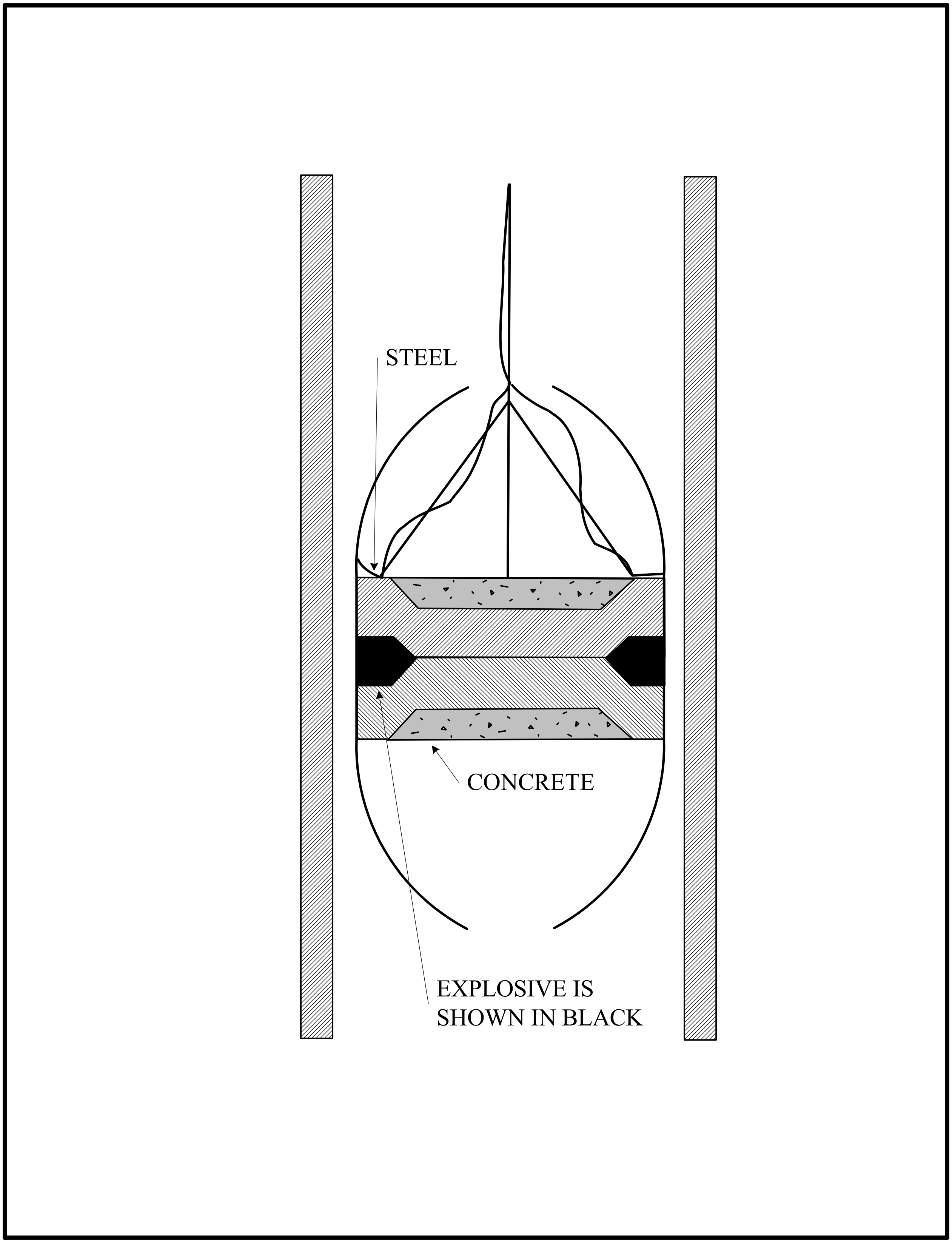

Figure 3.4. Focusing charge (From: DEMEX 2002).

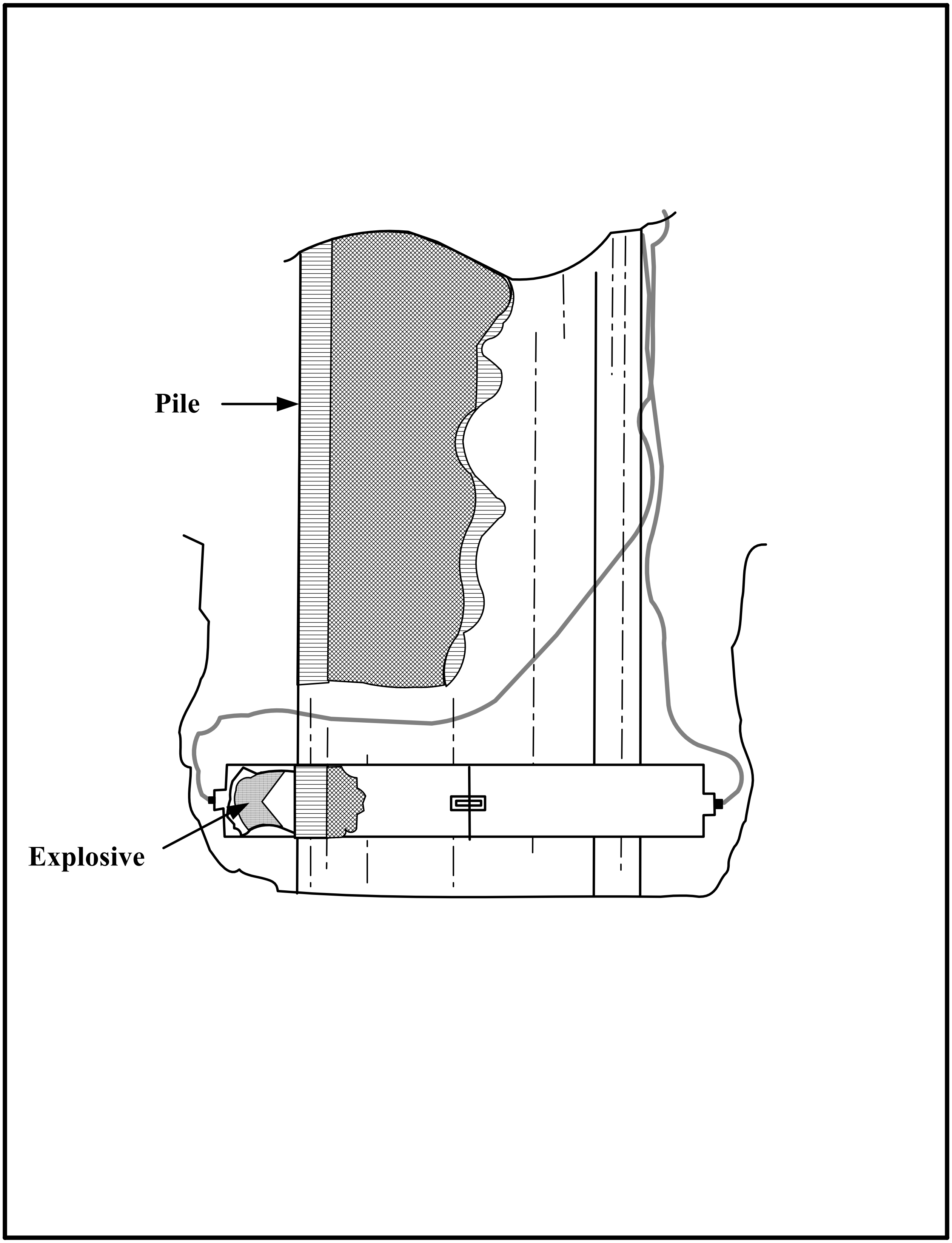

Figure 3.5. External linear-shaped charge (From: DEMEX 2002).

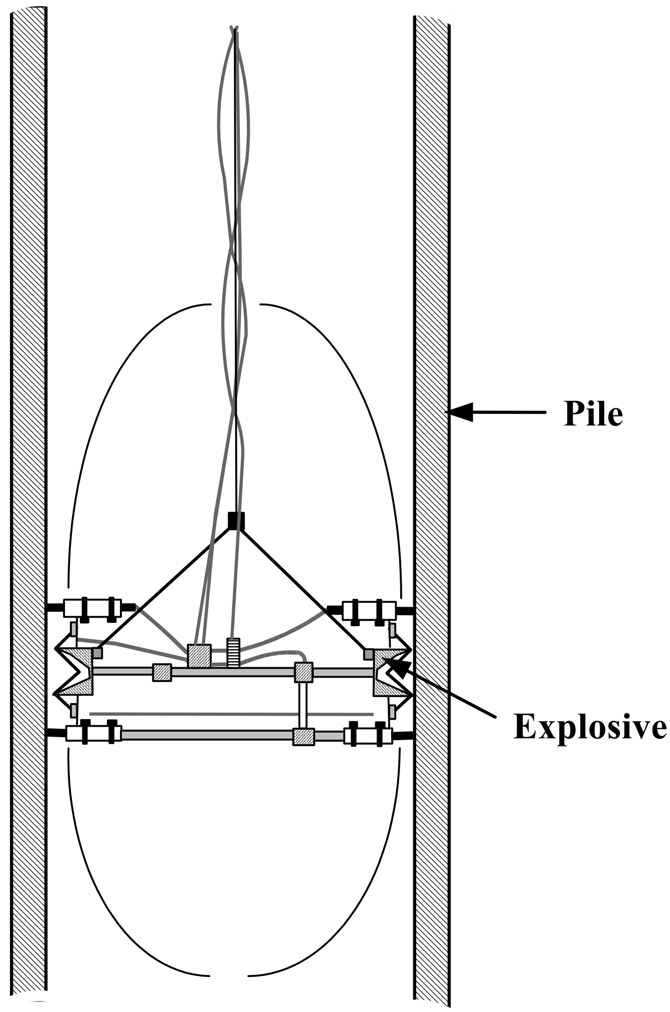

Figure 3.6. Internal linear-shaped charge (From: DEMEX 2002).

linear-shaped charges will not produce clean cuts. If linear-shaped charges are placed on the outside of a piling, any attenuation in the explosive force offered by the soil is lost. To be used on the inside of a piling, linear-shaped charges must be articulated to pass by the stabbing guides, and if a stabbing guide is located at the elevation of the proposed cut, a clean cut cannot be obtained. Also, if water or soil infiltrates the air space of the stand-off distance, charge performance is greatly reduced.

Cutting Tape

Explosive cutting tape is a flexible version of the linear-shaped charge (**Figure 3.7**). The explosive and the liner are extruded into a shaped charge housed in a flexible conductor that allows the tape to be contoured to the pile, thus maintaining the proper stand-off distance around the entire pile.

The disadvantages of cutting tape are two-fold:

1) Divers are required to place the tape around the target pile; and
2) Because the charge and liner are positioned in the conductor at the surface, at depths greater than 91 m (300 ft), ambient pressure may cause the conductor to deform, thus changing the stand-off distance and reducing the charge cutting efficiency.

At this point in time, cutting tape is not as efficient as linear-shaped charges for platform removal, especially at depths greater than 91 m (300 ft) (NRC 1996).

3.3 Potential Future Explosive Cutting Techniques

3.3.1 Contact Plaster Charges

Contact plaster charges are placed directly on the steel pile to be cut. The explosion causes a pressure wave to propagate through the pile thickness, and spalls or fragments some of the steel on the opposite side of the pile when it is reflected as a tensile wave. Pressure from the expanding gas completes the cut. This type of charge would reduce the charge weight but would have to be deployed in a cutting tape form by a diver. Shock refraction charges are the same size as plaster charges but are shaped like a shaped charge in cutting tape form. With shock refraction charges, compressibility is not a factor because the explosive is placed directly against the steel piling. There is no stand-off distance requirement because the pressure wave does the cutting. Diver placement is still required.

3.3.2 Shock-Wave Focusing Charges

Shock-wave focusing charges (**Figure 3.8**) are hollow charges flexible enough to be wrapped around tubular platform members internally or externally. These charges focus the energy of the shock-wave through a steel piling, and by exerting very high compressive/tensile stresses on the target area, initiate controlled brittle fracturing.

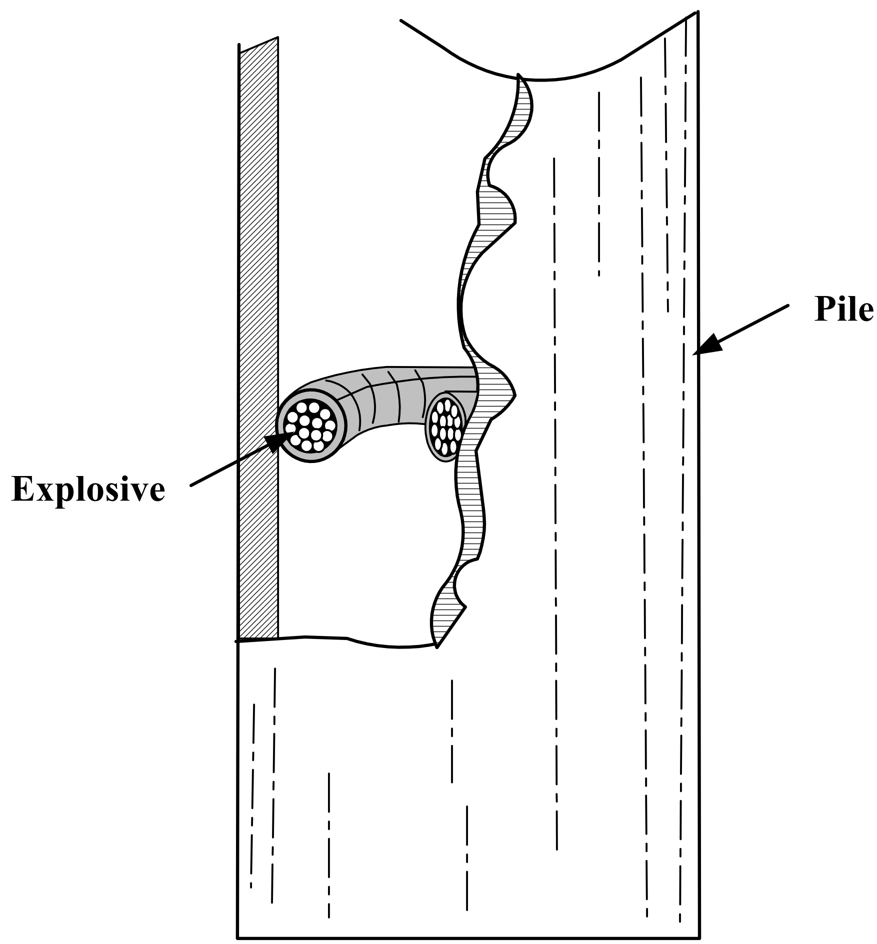

Figure 3.7. Flexible linear-shaped charge (From: DEMEX 2002).

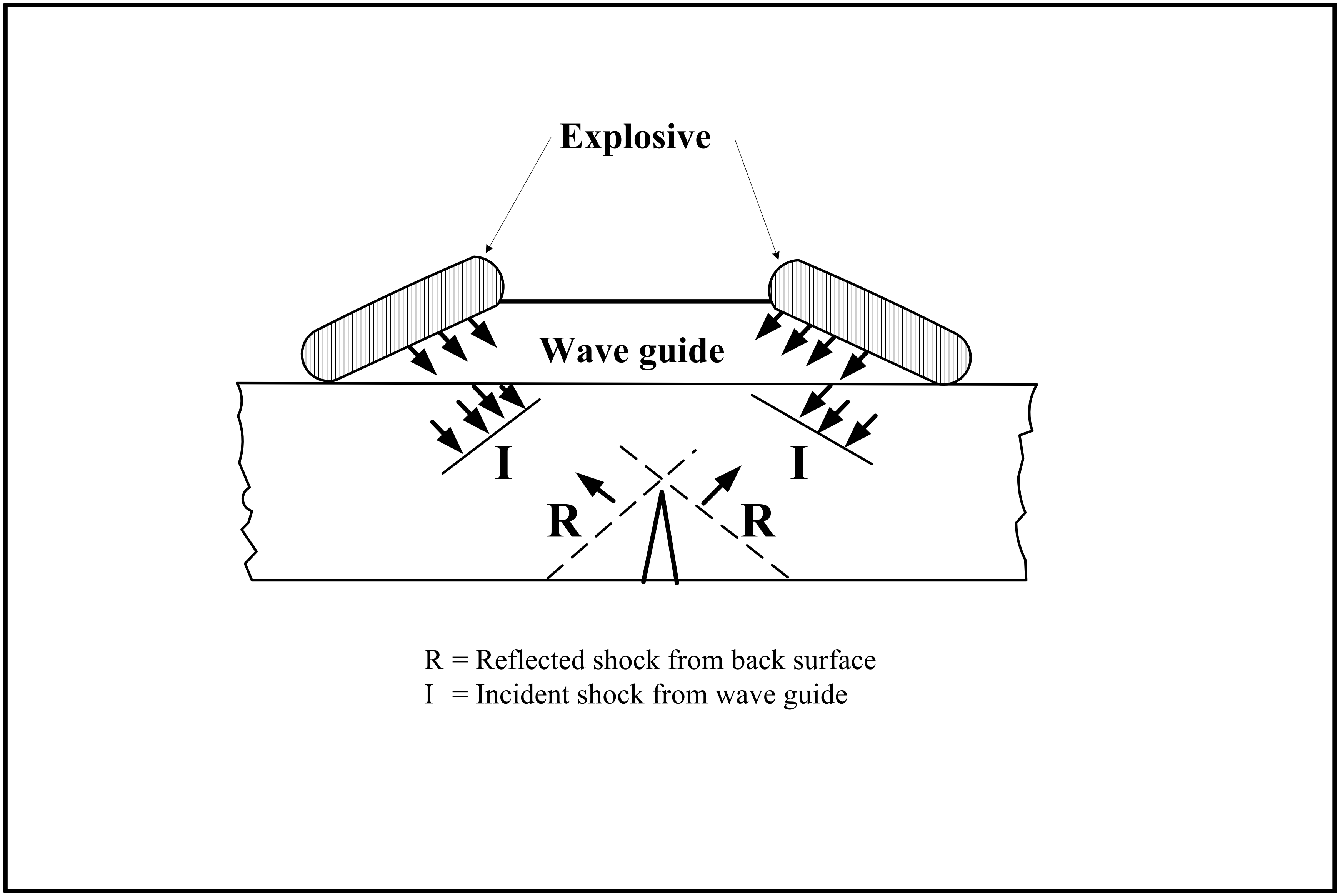

Figure 3.8. Shock-wave focusing charge (From: National Research Council 1996).

Shock-wave focusing can reduce the explosive weight of a cutting charge by up to 90% when compared with standard shaped charges. Shock-wave focusing charges are particularly effective for targets with thicker walls, but to be effective, they require that the opposite surface be backed by either water or air. Grout-backed surfaces are not effectively severed by shock-wave focusing methods.

3.3.3 Radial Hollow Charges

Radial hollow charges (**Figure 3.9**) are short, linear-shaped charges bent into an arc with the explosives initiated simultaneously at the central axis. The detonation front runs radially outward, detonating the explosive simultaneously on both sides of an inverted v-shaped liner. The liner collapses, producing a flowing radial cutting jet. Because of this diverging flow, a relatively long cut can be produced in a flat or curved steel plate. By joining a number of these types of charges together, it is possible to cut along plates and around pipes using relatively low explosive weights (**Figure 3.10**).

3.4 Characteristics and Physical Properties of Various Explosives

There are hundreds of commercially available explosives and many variations in the chemical mixtures of particular types of explosives. **Table 3.1** lists the physical properties of some of the more commonly used explosives. The physics of explosives are discussed in detail in the following chapter (**Chapter 4**).

3.5 Developing Technologies

Developing technologies within the industry include both modifications to explosives and improved mitigation methods. Explosives and explosive devices evolve based on market needs and regulatory requirements. Several potential improvements in explosives and explosive devices are listed below.

3.5.1 Improved Explosives

Manufactures are continually developing new and improved explosives. Applying these new types of explosives to the offshore industry may be one way to reduce charge size and minimize environmental impacts in the future. At the present time many new explosive compounds are manufactured in such small quantities that their large-scale use is cost prohibitive.

3.5.2 Improved Shaped Charges

Several design improvements in shape charges are in the testing phase. Currently a 5-lb charge limit would be limited to severing a tubular 36 inches or less in diameter.

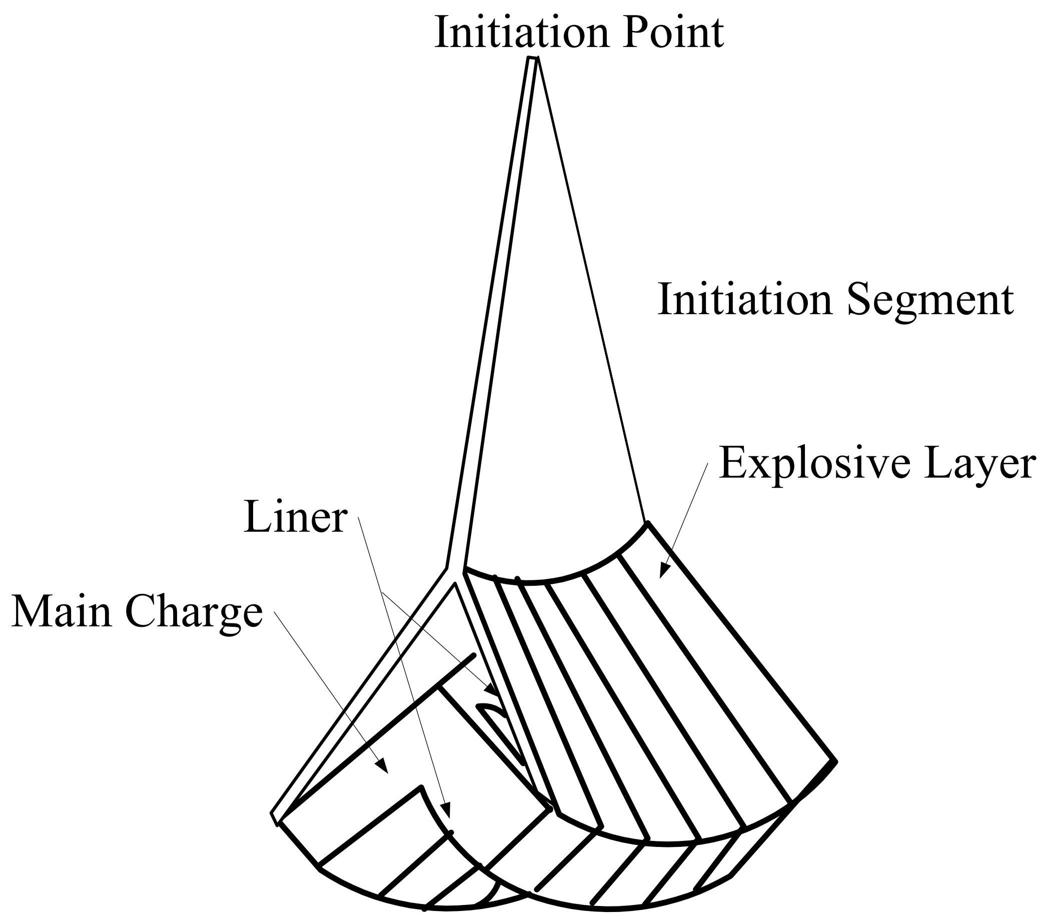

Figure 3.9. Schematic of a radial hollow charge (From: National Research Council 1996).

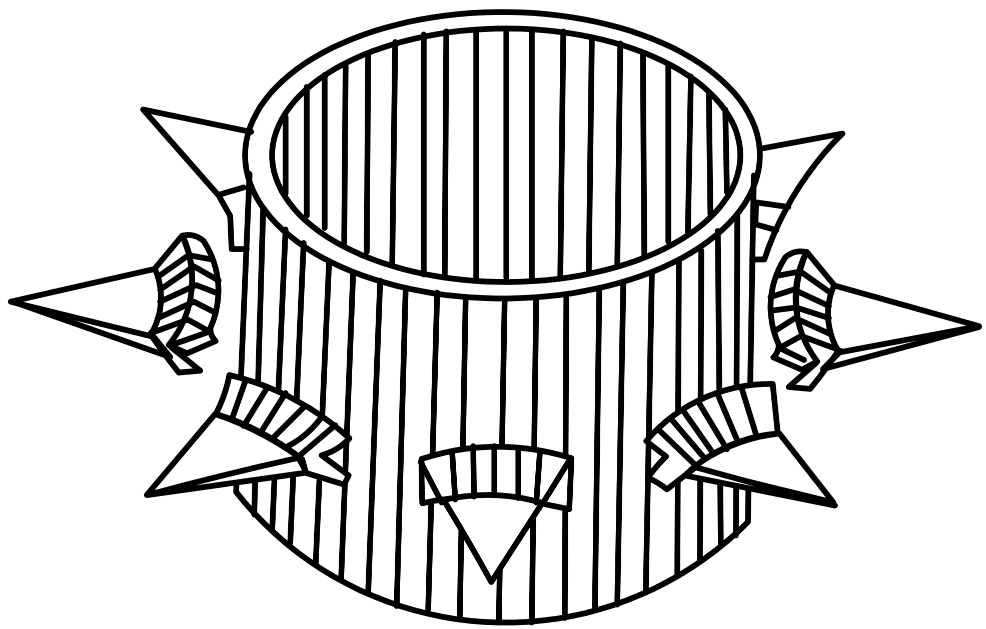

Figure 3.10. Radial hollow charges arranged for cutting a leg from outside (From: National Research Council 1996).

Table 3.1

Physical Properties of Some of the More Commonly Used Explosives (From: DEMEX 2002)

Explosive	Principal Use(s)	Velocity		Density	Shattering Effect (TNT = 1.0)	Water Resistance	Specific Energy (watts/kg)	Weight Strength %
		m/sec	ft/sec					
Black Powder								
Black Powder	Propellant	400	1,320	1.6	0.1	Poor	-	-
Primary Initiating Explosives								
Lead Azide	Detonator Primer	5,300	17,400	5	0.39	Fair	466	39
Diazodini – trophenol (DDNP)	Detonator Primer	6,600	21,700	1.63	0.92	Fair		76
Lead Styphnate	Detonator Primer	5,200	17,000	2.9	0.4	Fair	470	40
Secondary High Explosives								
Pentaeythritol tetranitrate (PETN)	Shape Charges Detonating Cord Metal Severance	8,400	27,600	1.7	1.73	Good	675	96
Cyclonite (RDX)	Demolition Charge Shape Charges Detonating Cord Metal Severance	8,750	28,700	1.76	1.57	Good	675	93
Homocyclonite (HMX)	Demolition Charge Shape Charges Metal Severance	9,100	29,800	1.91	1.45	Good	664	93
Trinitrotoluene (TNT)	Demolition Charge Shape Charges Cratering and Rock Removal Detonating Cord Metal Severance	6,900	22,600	1.65	1	Good	488	74

Table 3.1. Physical Properties of Some of the More Commonly Used Explosives (From: DEMEX 2002) (continued).

Explosive	Principal Use(s)	Velocity		Density	Shattering Effect (TNT = 1.0)	Water Resistance	Specific Energy (watts/kg)	Weight Strength %
		m/sec	ft/sec					
Ammonium Picrate (Explosive D)	Demolition Charge Shape Charges Metal Severance	7,150	23,500	1.6	1.25	Poor	321	70
Nitroglycerin (NG)	Demolition Charge Cratering and Rock Removal Propellant Metal Severance	7,600	25,000	1.81	1.81	Fair	720	96
Nitroglycol (NGC)	Demolition Charge Cratering and Rock Removal Propellant Metal Severance	7,300	24,000	1.48	2.06	Fair	780	105
Nitromethane (NM)	Demolition Charge Propellant Metal Severance	6,290	20,700	1.14	1.33	Fair	533	86
Tertiary High Explosives								
Ammonium Nitrate	Cratering and Rock Removal	2,800	9,200	1.13	0.6	Poor	280	52
High Explosive Compositions								
Composition B	Demolition Charge Shape Charge Metal Severance	7,840	25,700	1.68	1.3	Good	-	-
Composition C-4	Demolition Charge Shape Charge Metal Severance	8,040	26,400	1.59	1.32	Good	-	-

Table 3.1. Physical Properties of Some of the More Commonly Used Explosives (From: DEMEX 2002) (continued).

Explosive	Principal Use(s)	Velocity		Density	Shattering Effect (TNT = 1.0)	Water Resistance	Specific Energy (watts/kg)	Weight Strength %
		m/sec	ft/sec					
Cyclotol 70/30	Demolition Charge Shape Charge Metal Severance	8,060	26,450	1.73	1.31	Good	-	-
Octol 75/25	Demolition Charge Shape Charge Metal Severance	8,643	28,350	1.81	1.16	Good	503	-
Plastic Bonded (PBX9404)	Demolition Charge Shape Charge Metal Severance	8,800	28,900	1.86	1.37	Good	-	-
Pentolite 50/50	Demolition Charge Shape Charge Metal Severance	7,465	24,500	1.66	1.22	Good	588	-
Detasheet	Demolition Charge Metal Severance	7,300	24,000	1.62	1.12	Good	495	-
Torpex (Aluminized Explosive)	Demolition Charge Shape Charge Metal Severance	7,500	24,600	1.81	1.64	Good	867	-
Blasting Gelatin	Demolition Charge Shape Charge Metal Severance	7,300	24,000	1.5	1.91	Fair	740	100
HTA-3 Aluminized Explosive	Demolition Charge Shape Charge Metal Severance	7,870	25,800	1.9	1.19	Good	573	-
Commercial Dynamites								
40% NG Dynamite	Cratering and Rock Removal	-	-	-	-	Fair	-	40

Table 3.1. Physical Properties of Some of the More Commonly Used Explosives (From: DEMEX 2002) (continued).

Explosive	Principal Use(s)	Velocity		Density	Shattering Effect (TNT = 1.0)	Water Resistance	Specific Energy (watts/kg)	Weight Strength %
		m/sec	ft/sec					
50% NG Dynamite	Cratering and Rock Removal	-	-	-	-	Fair	-	50
60% NG Dynamite	Cratering and Rock Removal	-	-	-	-	Fair	-	60
Binary Explosives								
Binex 42P	Demolition Charge Cratering and Rock Removal	4,000	13,125	1.5	-	Good	-	
PLX (Liquid, Liquid)	Demolition Charge Shape Charge Cratering and Rock Removal Metal Severance	6,200	20,340	1.14	1.27	Good	535	85
Kinepak (Solid, Liquid)	Demolition Charge Cratering and Rock Removal Metal Severance	6,100	20,010	1.15	-	Good	-	80

3.5.3 Improved Charge Deployment Devices

Charge deployment devices are at the root of many of the problems discussed previously concerning charge placement and effectiveness. Unfortunately, since charge deployment devices are essentially expendable (being blown up with the charge), large investments in their development are rarely undertaken. The market for sophisticated, expensive charge deployment devices is limited.

3.5.4 Computer Modeling

There are several computer modeling developmental programs aimed at developing a better understanding of the best way to induce tubular failure. Once perfected, such computer modeling programs may allow contractors to better calibrate their explosive requirements and reduce the size of charges required for specific jobs.

3.5.5 Improvements in Explosive Cutting Tape

Explosive cutting tape is a type of linear shape charge. The flexibility of the tape allows it to be contoured to irregularly shaped platform members and still maintain the required stand-off distance for an effective cut. At the present time, the compressibility of this type of flexible linear charge makes it ineffective in deeper water where the hydrostatic pressure causes the liner to be distorted or collapsed. Improvements in the flexible casings for these types of charges could allow them to be used at greater depths.

3.5.6 Fracturing Charges

"Plaster" and "Shock Refracting" charges do not require the specific stand-off distance of a shaped charge, thus avoiding the compressibility problem. Charge weight for specific tubular cuts currently is difficult to calculate, but improvements in computer modeling may help with this problem. At the present time, these charges must be deployed by divers, making them difficult and expensive to use in deep water. There is the potential that ROVs and autonomous underwater vehicles (AUVs) could be employed or specifically developed to deploy these type charges in very deep water.

3.5.7 Shock-wave Focusing Charges

This method produces very high compressive stresses on the target material, which rapidly converts to tensile stress, and causes controlled brittle fractures. Tests conducted in air suggest that explosive weights required to cut specific size tubulars could be reduced as much as 90% compared to bulk charges using this method. This method requires the side of the target opposite the charge be backed by air. Because of this requirement, it is thought that shock-wave focusing charges will be ineffective at greater depths.

3.5.8 Radial Hollow Charges

Use of radial hollow charges would allow a low explosive-to-target ratio because they produce a diverging energy flow allowing a long cut on curved surfaces. However, this type of charge is difficult to place in deep water.

CHAPTER 4
PHYSICS OF UNDERWATER EXPLOSIONS

4.1 Underwater Explosive Source Characteristics

4.1.1 Explosive Process

The majority of explosives used in underwater demolition work contain oxygen in their molecules in a relatively unstable chemical bond. When the explosion is initiated, this oxygen is readily freed and recombines with other atoms to form more stable molecules. The explosive reaction is the breakdown of the original molecules into derivatives, a process accompanied by the release of large amounts of heat.

Detonation and burning, or deflagration, are the two forms of energy release that can take place, depending on the formulation and conditions of the blasting product. Detonation is the term for the rapid movement of a pressure front ahead of the chemical transition front. Formulations such as cyclonite (RDX) and trinitrotoluene (TNT) are properly referred to as explosives as they are intrinsically capable of detonation. The former is an example of a primary explosive, for which detonation can be achieved even in a small quantity of material with a nominal supply of energy such as that from a detonator cap. The latter is qualified as a high explosive (dynamite being another) in that it can achieve and sustain detonation only when the charge exceeds a critical volume or diameter.

The term blasting agent refers to a material that can be made to detonate when initiated properly, such as ammonium nitrate with fuel oil (ANFO) and water gel slurries. Blasting agents, like high explosives, require a minimum charge diameter for detonation – 50 mm diameter with confinement for ANFO, versus less than 20 mm diameter for some dynamites (Dick et al. 1993). The process of burning or deflagration is a slower release of the chemical energy of the materials, which does not cause a rapidly expanding detonation pressure wave. High explosives and blasting agents deflagrate when their charge diameter or volume is less than the critical threshold for detonation. Materials such as black powder, commonly categorized as low explosives, only deflagrate regardless of charge size and initiation conditions.

In a detonating explosive, a physical shock front rapidly compresses the explosive material and advances significantly faster than the sonic velocity of the material. As this front passes through the explosive, it triggers the release of chemical energy and thus realizes a self-sustaining wave that builds up to a stable limiting rate of propagation that is characteristic of the detonating material. This self-sustaining wave, known as a detonation wave, differs from a shock wave propagating through a non-reacting medium in that the conditions behind the shock front are affected by the energy released by the chemically transformed matter, and the wave is driven not by the motion of a boundary surface some distance behind the shock but by the internal conditions of the material immediately behind the front. This process is only sustained within the limits of the explosive material, and ceases at the boundary with the medium containing the explosive. A conventional shock wave then passes into the surrounding medium.

Beyond a short distance from the blast, generally taken to be three to ten diameters of the explosive's charge, thermal and direct detonation effects from the explosion can be ignored; the main sources of impact outside this distance are the shock wave and the expanding gaseous reaction products. The original shock wave is the primary cause of harm to aquatic life at great distances from the shot point; the expanding gases, if they do break into the water column from the substrate where the explosion occurs, can set up a pulsating bubble whose recurring pressure waves may also contribute significantly to damage. These phenomena will be discussed in later sections in the context of their relevance to the process of explosive removal of structures; a more exhaustive and general treatment of underwater blasting may be found in Cole (1948).

4.1.2 Shaped Charges and Directionality

In operations of explosive removal of offshore structures, most of the structural members to be severed are cylindrical metal structures protruding from the bottom sediment; these can be support legs, piles, or well conductors. The use of shaped charges, especially linear-shaped charges, is a well-established method (Al-Hassani 1988) for applying maximum cutting power to the surface of the object while minimizing the dispersion of explosive energy in ineffectual directions. A linear-shaped charge is a high explosive contained behind a metal sheath liner in the shape of an inward wedge; in tubular structure cutting, the charge is curved into a ring that fits either inside or around the structure so that the liner forms a V-shaped groove facing the surface to be cut. On detonation, the liner collapses and is projected toward this surface as a high-velocity metal jet traveling at about 2-3 km/s. The jet tends to converge and concentrate the energy onto a thin cutting line. One of the major challenges in the underwater use of shaped charges is the requirement for an air medium along the path of the cutting jet, as the efficiency drops significantly if the jet must pass through even a short distance of water. This is usually accomplished by incorporating an air chamber between the charge and the target surface in the design of the explosive casing.

A related method that, while not actually involving a shaped charge design, also makes use of detonation front dynamics to increase cutting effectiveness is the simultaneous detonation at both ends of a cylindrical charge lowered inside a casing (Al-Hassani 1988). In traditional underwater blasting of a solid substrate for material clearing, the practice is to initiate the shot at the deepest point of a charge inserted in a hole drilled in the rock (Keevin and Hempen 1997). The detonation front then propagates up the explosive column, focusing the shock energy primarily in that direction, with less energy being transmitted radially and only a small percentage emanating opposite the detonation direction (Konya and Walter 1985). For the purpose of cutting a tubular casing with a severance charge, on the other hand, the greatest effectiveness is achieved by initiating a detonation front at each end of a cylindrical charge. The two fronts meet at the center of the charge and produce double the impulsive pressure responsible for cutting through the surrounding metal wall, effectively focusing the energy release toward a smaller target area, much like a shaped charge would.

From the standpoint of environmental effects mitigation, these detonation techniques are advantageous in that they enable explosive structure cutting work to be performed with smaller charge weights and thus with less overall release of energy in the surrounding medium. The directionality pattern of the acoustic levels in the far field, however, is not appreciably affected by the shaped-charge detonation dynamics and is chiefly dependent on the overall geometric dimensions of the charge relative to the wavelength of sound at frequencies of interest. For the purpose of discussing directivity, we can assume that all sections of the charge detonate simultaneously. Directionality functions in the plane of charge distribution can be readily computed for a line charge and for a uniform rectangular charge configuration. The line charge directivity is given by

$$D(f,\theta) = \frac{\sin u}{u}, \quad \text{where} \quad u = \pi f L \frac{\sin\theta}{c},$$

L is the length of the line, and θ represents the angle measured from broadside (at right angles to the line). The directivity function for a rectangular distribution is the product of the directivities of two perpendicular line charges, which gives

$$D(f,\theta) = \frac{\sin u \sin v}{uv}, \quad \text{where} \quad u = \pi f L_1 \frac{\sin\theta}{c}, \ v = \pi f L_2 \frac{\cos\theta}{c},$$

and L_1 and L_2 are the length and width of the rectangular charge. For the circular explosive distribution of the charges used for pile cutting, as intuition would suggest, there is no acoustic directionality in the horizontal plane. In the vertical plane, the acoustic level at a given frequency will exhibit a significant directivity pattern only if the linear size of the charge is comparable to the acoustic wavelength in the medium; directionality will therefore always diminish at lower frequencies. At a sound frequency of 750 Hz, the wavelength is approximately 2 m in water and longer yet in a mud layer with higher acoustic velocity, meaning that only charges having geometric dimensions of that order will exhibit appreciable vertical directionality. This would be the case with the ring charges used for severing tubular platform legs that can be several meters in diameter. As ring charges are installed horizontally to cut risers, the highest sound levels will be projected in the water column directly above them — the main directional lobe being broadside to the plane of the ring. The acoustic levels measured in the water column off the vertical would then be lower than predicted on the basis of propagation range alone.

4.1.3 Media Considerations

The location of the explosive in the surrounding media is of the greatest influence in determining the acoustic levels generated in the water column by an underwater detonation. Open-water shots, in which an unconfined explosive is detonated within the water column itself, are not part of the current practice for explosive removal of offshore structures, as regulations specify a minimum depth of 5 m (15 ft) below the mud line for any charge used to sever a structural component (Richardson 1989). The acoustic impact of the buried charge explosion, however, can vary significantly depending on the nature of the sediment and could range in principle from an essentially waterborne detonation to a completely confined shot with no venting of explosion gases into the water column. The presence of the metal structure being severed, which may act as containment and will absorb a portion of the explosive energy, further complicates the scenario compared to the detonation of a free charge in the sediment. Generally it is safe to assume that ignoring the effects of the structure will yield a conservative "worst case" assessment of the impact from the detonation, and there is evidence (Nedwell et al. 2001) that the extremely high detonation forces in close proximity of the charge so far exceed the strength of the metal structure as to make its influence negligible.

The physics of shock and acoustic wave propagation from a detonation will be presented in a later section. Here we want to introduce empirical relations that predict the acoustic level at a given range from the detonation in order to discuss how the positioning of the charge in the sediment layer alters the expected impact relative to the open-water case. For a detonation in the free water column, assuming no source directionality effects, the peak pressure in the near-field is given in terms of the range *r* in meters and charge weight *W* in kilograms by the well known relation

$$p_0 = 5.24\times10^7\left(\frac{W^{1/3}}{r}\right)^{\alpha} \quad \mathrm{N/m^2},$$

where the exponent α is the attenuation coefficient in water, $\alpha \approx 1.13$. A derivation based on ray theory (Powell 1995) extends this relation to the case of peak pressure from a charge buried a distance *b* below the sediment surface, measured at a point distance *a* above that surface (*r* still being the slant range between source and measurement point):

$$p_0 = 5.24\times10^7\left(\frac{W^{1/3}}{r}\right)^{\varepsilon}\left(\frac{a+b}{b}\right)^{\varepsilon-\alpha} \quad \mathrm{N/m^2},$$

where ε is the bottom attenuation coefficient. Based on full-scale measurements carried out by Connor (1990) during a Gulf of Mexico platform removal, Powell (1995) estimated $\varepsilon \approx 1.99$ for a compact mud bottom. It is readily observed that the above formula correctly reverts to the open-water case in the limit for $\varepsilon \to \alpha$ (the sediment attenuation tends to that of water). This also signifies that in low-density sediments, the influence on peak pressure of deploying the charge below the mud line could be insignificant, a fact borne out by field measurements during a North Sea platform removal operation (Nedwell et al. 2001) where the peak pressure in the water column from pile-cutting detonations below the sediment surface was found to match the open-water estimates. The equation above provides a more definite estimate of peak pressure in the water column due to explosions below the mud line than the often taken approach of merely bracketing the estimate between the value for an open-water shot and that for a fully confined explosive embedded in rock (generally taken to be 5% to 10% of the open-water case). The expression also is consistent with the physics of wave transmission at the bottom-water interface as, for a given range between source and receiver, the peak pressure estimate increases with receiver height above the bottom. This can be seen to correspond to the increase in energy coupling efficiency as the angle of incidence approaches the normal.

4.1.4 Multiple Charges

The practice of cutting several of the supporting piles of a platform by detonating multiple charges at once was adopted in the past as an efficient removal procedure. Al-Hassani (1988) mentions a 1983 decommissioning operation in the Gulf of Mexico in which all the piles were cut simultaneously by linear-shaped charges, causing the conductor to settle on its mud mats to be later floated using buoyancy tanks. This type of procedure was since prohibited by operational restrictions introduced in 1988 that include a minimum delay of 900 milliseconds between detonations as well as a limit of eight detonations in a group (Richardson 1989). Nonetheless, it is important to examine briefly how multiple detonations contribute to the overall pressure levels in the water column.

In the acoustic approximation, where it is assumed that the pressure front from the detonation has decayed sufficiently in strength to propagate as a sound wave, the pressure at any point through which two waves from different sources overlap is simply the sum of the independent pressures from each disturbance. The argument does not apply to the combination of shock waves in the near-field of two detonations, because the properties of one shock front will change as it propagates through fluid that has already been affected by another shock. This leads to the formation of reflected shocks and the creation of regions of significantly higher overpressure than would be found behind a single shock. In the practice of underwater detonation for structure removal, however, such shock interaction phenomena would only affect a relatively small region in the proximity of closely spaced and simultaneously exploded charges. For the majority of the propagation volume, the acoustic approximation would apply.

When estimating the acoustic pressure levels from simultaneous or nearly simultaneous detonations, the relative positions of the respective charge locations should be considered. When the charges are spaced at greater distance than a few wavelengths for the specific frequencies of interest (the spectral regions where acoustic energy is strongest), then the resulting energy flux density (EFD) levels in all directions can be assumed to be simply the sum of the individual EFDs (incoherent sum). If the charge spacing is less than or comparable to a wavelength, then a coherent approach should be taken. This involves treating the distribution of charges as an acoustic array that has directional characteristics. The incoherent sum of EFDs must then be corrected using the system directivity function. Although the pattern of directional lobes depends on the array geometry, as a rule the directions of strongest output will be perpendicular to planes in which the charges lie. If in the operation mentioned earlier the legs of the platform were cut by simultaneously detonated charges all at the same depth, the directions of maximum sound output would be straight up and down. With the regulatory limitation of nearly 1 second minimum interval between detonations, on the other hand, such considerations are no longer of practical concern as the sound level pattern from a single charge would not be affected by the interaction with others.

4.2 Shock Wave and Acoustic Propagation

The manner in which shock and acoustic waves propagate from the source into the ocean is strongly influenced by the ocean environment. Noise propagating in shallow water environments, where depth is less than a few hundred meters, can reflect many times from the sea surface and bottom. In these cases, sea surface roughness and sea bottom characteristics are often very important. Fewer surface and bottom interactions occur in deeper water. However, refractive effects due to differential temperature and salinity profiles can cause sound to be trapped in small depth channels and can lead to sound focusing. This section discusses how sound produced by removal operations propagates away from the operation site and ensonifies the surrounding sea.

4.2.1 Pressure Waveform

The pressure wave of underwater explosive detonations is composed of a shock or primary pulse followed by a series of bubble pulses. The shock pulse has rapid rise time and exponential decay, as is discussed in following subsections in this chapter. This high-pressure pulse is due to the rapid conversion of solid explosive to gaseous form. The gas bubble initially expands due to its very high pressure. It eventually reaches and overshoots the volume corresponding to ambient water pressure due to the radially outward momentum imparted to the surrounding water. The negative-phase pressure following the shock pulse is due to the overshoot. Eventually the bubble reaches a maximum volume, corresponding with the minimum of the negative phase, and then starts to collapse. It reaches a minimum volume that corresponds with a second peak in the pressure waveform, referred to as the first bubble pulse. This oscillatory behavior continues, albeit with successively lower amplitude pulses as energy is lost to heat dissipation. **Figure 4.1** shows the recorded waveform from a 0.82 kg charge detonated at 193 m depth. It clearly shows the features of the explosive waveform described here.

4.2.2 The Near-Field

The near-field is the region close to the detonation location where the pressure wave has sufficiently high amplitude that particle displacements are not always proportional to pressure. In this region, the shock pressure front pre-conditions the medium by heating and compression, so that acoustic waves behind it travel more quickly. The acoustic waves catch up to and reinforce the shock front, thereby sustaining its high pressure. The explosion pressure pulse is referred to as a shock wave in the region close to the source where the shock front persists. The shock pressure decreases in amplitude as it moves further from the source due to geometrical spreading and heat dissipation. The peak pressure eventually drops to levels at which the non-linear effects cease. Afterwards, all parts of the pressure pulse propagate at the same speed, and the signal is then referred to as an acoustic wave.

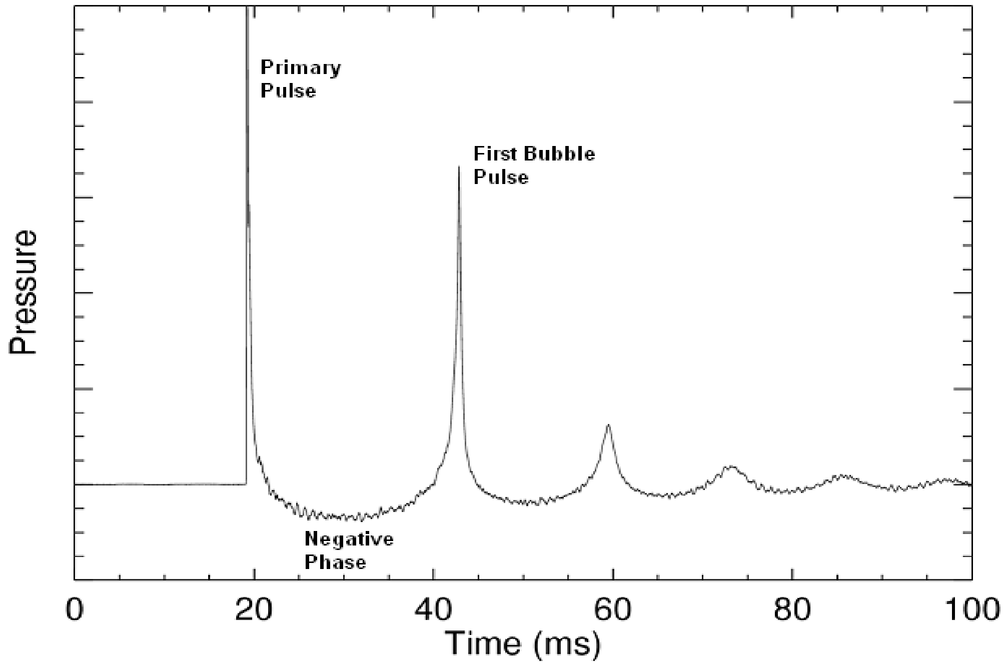

Figure 4.1. Pressure waveform from a 0.82 kg SUS charge detonated at 193 m (Reproduced from: Hannay 1995).

Measurements of pressure waveforms in the very near-field show that shock pulse pressure as a function of time $p(t)$ is described quite accurately by an exponentially decaying function of the form:

$$p(t) = p_0 \exp(-t / t_0)$$

where p_0 is the peak pressure associated with the shock front and t_0 is a time constant for exponential decay. Explosion shock theory has proposed specific relationships for the peak pressure and time constant in terms of the charge weight and range from the detonation position. These theoretical relationships have been confirmed by measurements of pressure waveforms from a wide variety of TNT charge detonations:

$$p_0 = 5.24 \times 10^7 \left(\frac{W^{1/3}}{r} \right)^{1.13} \quad \mathrm{N/m^2}$$

$$t_0 = 9.25 \times 10^{-5} W^{1/3} \left(\frac{W^{1/3}}{r} \right)^{-0.22} \quad \mathrm{sec},$$

where W is the charge weight in kilograms and r is the distance from the source in meters. These equations are valid only in the near-field of the explosion. A limiting range for their validity has been suggested to be $r_0 = 4.76 W^{1/3}$ meters (Gaspin 1983). At ranges greater than r_0, the expressions for peak pressure and time constant must be modified. Rogers (1977) proposed the following modifiers for peak pressure and time constant for $r > r_0$, based on weak shock theory:

$$p_0(r > r_0) = p_0(r_0)\{[1 + 2(r_0 / L_0)\ln(r / r_0)]^{1/2} - 1\} / [(r / L_0)\ln(r / r_0)]$$

$$t_0(r > r_0) = t_0(r_0)[1 + 2(r_0 / L_0)\ln(r / r_0)]^{1/2}$$

where $L_0 = \rho c^3 t_0(r_0) / [p_0(r_0)\beta]$, ρ is the density (≈1,026 kg/m^3 for sea water), c is the sound speed (≈1,500 m/s), $\beta = 3.5$, and $p_0(r_0)$ and $t_0(r_0)$ are computed from the near-field equations above.

4.2.3 Sea Surface Reflections

The smooth sea surface is a strong reflector of acoustic energy at nearly all frequencies. The reflection coefficient is close to negative one, indicating that 180-degree phase reversal occurs upon reflection. This means that incident pressure pulses will be reflected with reversed polarity. This effect is apparent in **Figure 4.2**, which shows the direct path and surface reflected signals from a charge detonated at 23 m depth. The waveform in this figure also exhibits the effect of cavitation, which can occur upon reflection of high-pressure shock pulses at the surface. Cavitation happens when the reflected pulse pressure drops below -1 atmosphere (-101 kPa). When this happens, the strongly negative pressure wave causes water to vaporize, creating small bubbles. The surface-reflected shock pulse signal in **Figure 4.2** is truncated due to this effect. It also is followed by a short period of high-frequency noise produced by oscillations of the cavitation bubbles. It is noted that the cavitation effect is not noticed in the surface reflections of the lower-amplitude bubble pulses in **Figure 4.2**.

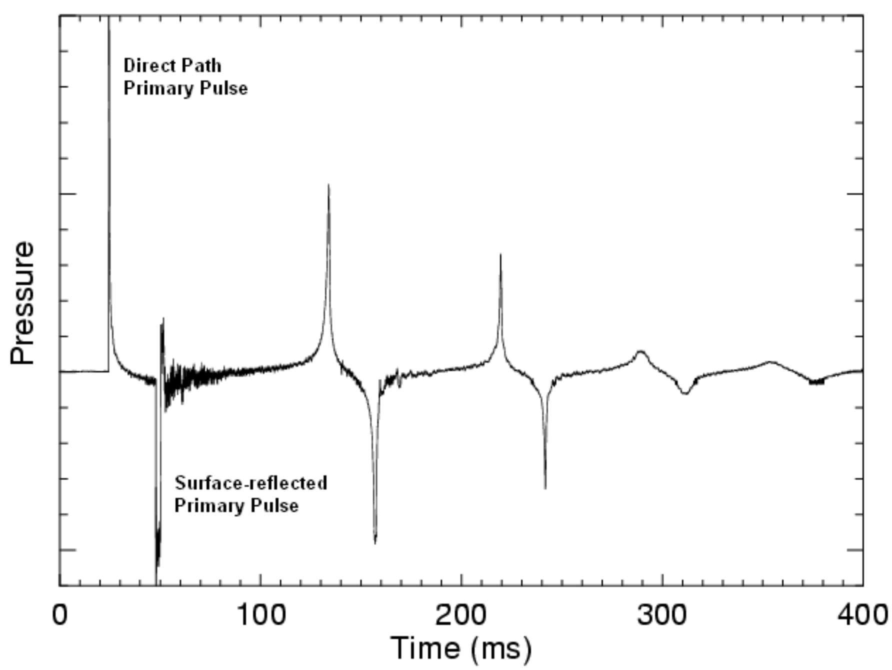

Figure 4.2. Pressure waveform for 0.82 kg SUS charge detonated at 23 m. Waveform shows reversed-polarity surface reflections (From: Hannay 1995).

Sea surface roughness causes scattering of sound upon reflection. Furthermore, entrapped bubbles near the surface due to breaking waves can absorb acoustic energy and also can scatter reflected energy. These effects tend to reduce the amplitude of the reflected signals. The scattering and absorptive effects of rough surfaces become important when the dimension of the roughness is comparable to or larger than the wavelength of the reflected sounds. Consequently, roughness generally has greater importance for high frequency (small wavelength) sounds than it does for low frequency sounds.

When the charge is detonated very close to the sea surface, the reverse-polarity surface reflected signals can cancel out the direct path signal. This is especially true in horizontal directions because the two propagation paths are nearly identical in length and consequently the two signals can arrive nearly simultaneously. If the charge is detonated at greater depths, then the two signals may partially overlap, causing either constructive or destructive interference. The source signal strength pattern is a function of angle measured from horizontal, frequency, and source depth. This interference effect is known as the Lloyd mirror effect (Officer 1958).

4.2.4 Sea Bottom Reflections

The sea bottom, or seafloor, is a reflector of acoustic energy. The impedance contrast between water and bottom materials, however, is less than between water and air at the sea surface. Consequently, a large fraction of acoustic energy incident on the seafloor will be transmitted into the bottom where it may reflect from subbottom layers. A full discussion of the physics of multi-layer reflections is beyond the scope of this report; however, an excellent synopsis may be found in Brekhovskikh (1980) (see "Waves in Layered Media" [Brekhovskikh 1980] for an in-depth treatment of this subject). For the purposes of the present discussion, it suffices to consider composite reflection coefficients that encompass the energy reflected from all bottom layers. Seafloor reflection coefficients range from about 0.1 to 0.5 at steep angles of incidence and can increase to nearly 1.0 at very shallow angles. Rough ocean bottoms tend to scatter energy, similarly to rough sea surfaces, thereby reducing the reflection coefficient for high frequency sounds. It is noted that the bottom reflection coefficient is real and positive at steep angles, but is often complex for shallow angles. Complex reflection coefficients distort the shape of the reflected wave.

4.2.5 Long-Range Propagation

Sound levels at significant distance from underwater explosions can vary considerably depending on the depth of the explosion, the depth of charge burial, and the characteristics of the ocean environment. Acousticians have simplified the propagation problem by introducing the sonar equations. A simplified version of the sonar equations divides the problem into three primary components: Source Level, *SL*; Transmission Loss, *TL*; and Received Level, *RL*. They are related through the basic equation:

$$RL = SL - TL$$

The source level indicates the strength of the source in decibels. It is by convention referenced to the sound level at 1 m from the charge. Normally, *SL* is determined by measuring or modeling the pressure at a practical distance, and then scaling this value back to 1 m range by adding a spherical spreading loss scaling correction, typically 20 log *r*, where *r* is the distance at which the measurement or model prediction is made.

TL is the parameter that quantifies how the medium reduces the sound level as the signal propagates from the source to the receiver. This parameter includes the effects of surface and bottom reflections, as well as any refractive effects occurring in the water itself. Prediction of *TL* can be a very complex problem because it is dependent on all characteristics of the sea surface, water column, and sea bottom as well as the locations of source and receiver relative to the bottom topography. Several computer codes have been developed specifically for predicting *TL* based on specific acoustic and geo-acoustic input parameters. These codes are referred to as propagation models and are based on several different mathematical approaches. Each of the presently available approaches has specific advantages and disadvantages, as summarized in **Table 4.1**.

Table 4.1

Acoustic Propagation Modeling Approaches and Their Respective Advantages and Disadvantages

Model Type	Approach	Advantages	Disadvantages
Ray Theory	Tracks rays perpendicular to wave fronts through the water.	Can model range-dependent situations in shallow or deep water, accurate for high frequency sound; provides time domain results. Gaussian Beam versions improve accuracy for low frequencies.	Less accurate than other methods for modeling low frequency refractive effects, especially near caustics (sound convergence loci) and for multi-layer bottom problems.
Normal Mode	Computes single frequency transmission losses by summing mode functions representing propagation resonances.	Accurate for low frequencies, very fast computation times for long range propagation, range dependence can be achieved under certain assumptions.	Not well suited for high frequencies and/or deepwater cases.
Wavenumber Integral	Computes transmission loss for single frequencies by decomposing the problem into plane wave components that can be solved analytically.	Accurate and fast for low frequencies and most depth regimes.	Handles range independent cases only; computationally expensive for very long ranges.
Finite Difference	Solves the wave equation on a computational grid by calculating derivatives of the pressure field directly.	Very well suited for range-dependent problems (see **Figure 4.3**); parabolic equation and split-step versions are computationally efficient for low frequencies.	Not well suited for high frequencies due to computational grid resolution restrictions.

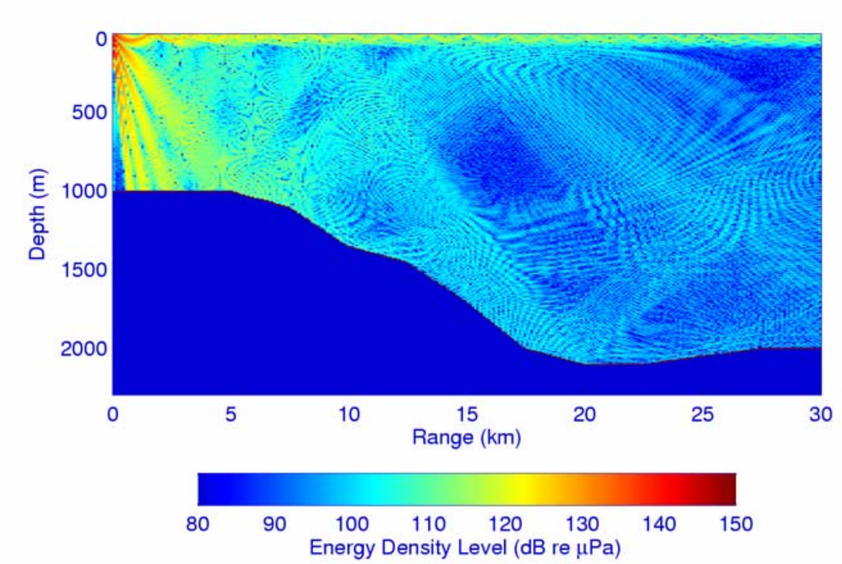

Figure 4.3. Example sound field calculations produced using the parabolic equation finite difference propagation model.

Alternate rule-of-thumb methods have been devised to obtain rough estimates of *TL*. For example, Marsh and Shulkin presented semi-empirical formulae for estimating TL in shallow water for frequencies between 100 Hz and 10 kHz (see Urick 1975). These formulae utilize tables of correction factors to account for frequency-dependent absorption and different sea-states and bottom types. The steadily increasing availability of fast computing platforms to perform detailed numerical modeling is making the use of these approximate estimation methods less and less justifiable in impact prediction studies.

4.3 Sound Metrics and Injury-Mortality Criteria

4.3.1 Metrics

Sound level metrics are parameters that quantitatively describe the characteristics of sound pressure waves at a given spatial location. The commonly used metrics for impulsive sounds describe the amplitude, energy and time-related characteristics of the pressure wave. The values of specific metrics are used to gauge the degree of impact that underwater sound signals have on marine wildlife. Standard thresholds for the metrics have been established in reference to the minimum levels at which specific impacts have been observed to occur for given species.

The metrics that need to be considered for gauging one type of impact may differ from the metrics used for another type of impact. For example, very high-amplitude pressure pulses, indicated by large values of the peak pressure metric, may cause differential tissue displacement that can disrupt cells and tissues. On the other hand, prolonged medium amplitude sounds, such as sounds from underwater drilling, can cause injury to hearing systems. The impact on hearing is better classified by the metrics root-mean-square (rms) and EFD.

Impulsive sounds arise from short duration events such as explosions and airgun shots. These sounds are characterized by relatively high amplitude, short duration pressure waveforms. The following are the most common metrics for impulsive sounds:

- Peak pressure: The highest pressure attained by a sound pressure signal. This pressure is measured with respect to ambient pressure, and also is referred to as zero-to-peak pressure.
- Peak-to-peak pressure: The difference between the highest pressure and lowest pressure over the duration of a waveform. For impulsive sounds produced by blasting, the lowest pressure is generally negative with respect to ambient pressure and occurs soon after the largest positive peak due to expansion imparted to the water by its positive impulse.
- Impulse: The time integral of pressure through the largest positive phase of a pressure waveform. It has units of Pascal seconds.
- Root-mean-square (rms): The square root of the mean square pressure over the duration of the impulsive waveform. The duration used strongly influences the value of this metric, though its definition is sometimes quite ambiguous. Recent methods have been proposed for determining the duration based on the cumulative EFD function.
- Energy flux density (EFD): The total acoustic energy propagated through a unit area normal to the direction of propagation. The EFD of plane waves can be computed as the time integral of squared pressure, divided by the acoustic impedance of the medium:

  $$\mathrm{EFD} = \frac{1}{\rho c}\int p^2 dt\ .$$

  For plane waves, the acoustic impedance is simply the product of sound speed c and density ρ. EFD has units $\mathrm{J/m^2}$. EFD is not suitable for continuous-wave sounds because the integral is not normalized in time. A similar metric, acoustic intensity, divides the expression by the integration time, thereby producing a metric having units of power per area. The above expression for calculating EFD is only valid for simple pressure fields that are not significantly influenced by sea surface and bottom reflections or refractive effects. However, it is often used when complex pressure fields are present. A more correct term for the result in those cases is the sound exposure level.
- Sound exposure level (SEL): The time integral of square pressure divided by the product of sound speed and water density. SEL is commonly expressed in decibels (dB) as described in the next section.

4.3.2 Decibels

All of the above metrics, except for impulse, are normally expressed in decibels. The decibel presents pressure values on a logarithmic scale relative to a pre-defined reference level. The sound pressure level *SPL* in decibels is related to the linear pressure p (representing either peak, peak to peak, or rms pressure) according to:

$$SPL(\text{dB}) = 20\log\left(\frac{p}{p_0}\right),$$

where p_0 is the reference level. The underwater sound level reference is 1 microPascal (μPa). Consequently, a pressure pulse with peak pressure of 1 μPa has a peak sound level of 0 dB. Sometimes this is expressed as 0 dB re 1μPa.

The EFD and SEL metrics are converted to decibels in a slightly different way. It is noteworthy that these 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. By looking at SEL, the conversion of both of these metrics to decibels can be demonstrated. If the SEL is computed as e (in units of J/m^2), then it is expressed in decibels according to

$$SEL(\text{dB}) = 10\log\left(\frac{e}{e_0}\right)$$

where e_0 is a reference SEL. This reference has been defined as the equivalent sound exposure produced by a 1 μPa rms plane sine wave over 1 second. Therefore, if signal pressure p is expressed in microPascals, then the SEL in decibels can be computed conveniently according to the following:

$$SEL(\text{dB}) = 10\log\left(\int p^2 dt\right).$$

For example: a 1 μPa rms sine wave, having a duration of 10 seconds, has an SEL of 10 dB re μPa. Some authors present this metric in units referenced to (μPa^2 s) or (μPa s$^{1/2}$) to indicate that the actual reference is based on a unit defined by the product of time and square pressure (in fact the square root of this product). A common alternate reference unit is 1 erg/cm^2, though that reference has become significantly less common with the transition from cgs units to SI. The relationship between SEL and EFD referenced to μPa s$^{1/2}$ and ergs/cm^2 is

$$\text{dB re } \mu\text{Pa} \cdot \text{s}^{1/2} = \text{dB re erg/cm}^2 + 152$$

4.3.3 Frequency Content

None of the above metrics directly provides information about the spectral energy content of the sound signal. Spectral content is important for some types of impact criteria. For example, an accepted threshold level for temporary threshold shift (TTS) is based on exceeding EFD levels of 182 dB re μPa^{2}s in any 1/3-octave frequency band (Department of the Navy 2001). The standard approach in this case is to apply frequency domain filtering to the pressure waveform prior to computation of the threshold. This approach is recommended only for the EFD (or SEL) and rms metrics. A modified version of the peak pressure metric has also been developed that accounts for the frequency-dependent hearing sensitivities of specific species. This metric, identified as dB_{ht}(Species), is described below.

4.3.4 dB_{ht}(Species)

The dB_{ht}(Species) metric expresses sound pressure levels relative to the hearing thresholds of specific species. It is used most commonly for gauging impacts of continuous sounds, although it also may be applicable for impulsive noise. This metric also is referred to as dB_{ha}(Species) as defined by Nedwell et al. (1999), where “ha” represents hearing ability. The dB_{ht}(Species) metric is based on the same principle as frequency weighting schemes used for determining impacts of noise on humans. The approach is to filter the pressure time series using a filter that represents the frequency-dependent sensitivity of hearing for the species of interest. Measurements of hearing sensitivity versus frequency for individual species are known as audiograms. Audiograms have been measured for many species of fishes and a limited number of whales. Confidence in the accuracy of audiograms for most marine species is, however, limited at the present due to the small number of individuals upon which these measurements have been performed.

The dB_{ht} metric is computed by first filtering the pressure function according to the frequency sensitivity of the species of interest. The resulting time series is analyzed to determine the peak or rms sound pressure level. A level of 0 dB_{ht} should be just audible, i.e., at the hearing threshold of the species. Since most audiograms are determined using non-impulsive sounds, we might expect that impulsive or very short-duration sounds may have to possess peak levels greater than 0 dB_{ht} in order to be perceived. It is also noted that dB_{ht} is not an absolute sound level unit. Rather, it provides a measure of the perceived sound loudness.

When applying the hearing threshold audiogram measures to a potentially injurious sound or shock wave, one should be cautious about injury caused by mechanisms other than those having to do with hearing. Consider an animal with poor hearing at low frequencies being exposed to an extraordinarily high sound pressure at low frequencies. The audiogram-based dB measures will be much lower than the absolute pressures and could mislead people into believing that injury was unlikely.

We note finally that sound pressure level metrics for humans are based not only on frequency-weighted scaling, but also on time weighting. Integrating sound level meters perform “slow” or “fast” time weightings as standard practice in computing EFD or SEL metrics. The integration intervals are limited to windows of 1-second (slow) and 1/32-second (fast) during computation of the EFD. This type of time weighting does not appear to be discussed in the marine mammal literature for computing dB_{ht}.

4.3.5 Impulse

Impulse I is defined by the time-integral of pressure through the waveform. The impulse for exponentially decaying shock pulses from underwater explosives (assuming no interference with surface or bottom reflections) is given by the simple expression $I = p_0 t_0$, where p_0 is the maximum pressure and t_0 is the time constant. However, for shallow sources or receivers, the arrival of the surface reflection has the effect of canceling later parts of the direct path shock pressure pulse. Consequently, impulse calculations are often performed by integrating the direct path pressure only up to the arrival time of the surface reflection. The time difference T_s between the direct path and surface reflection can be calculated easily if straight-line propagation of these paths is assumed:

$$T_S = \frac{1}{C_0}\left\{\sqrt{R^2 + \left(Z_s^2 + Z_r^2\right)} - \sqrt{R^2 + \left(Z_s^2 - Z_r^2\right)}\right\},$$

where C_0 is the sound speed in the water, Z_s and Z_r are the source and receiver depths, and R is the horizontal distance between source and receiver.

Goertner (1982) has further modified the integration time by noting that lung damage in marine mammals occurs primarily from oscillation of the lung cavity. Goertner's integration period for calculating impulse is the lesser of the surface reflection delay and the oscillation period of the lung. Goertner's model is proposed only for marine mammals and is not valid for fishes. According to Goertner's approach, modified for Standard International units, the lung volume in liters at the surface (pressure = 101.3 kPa) is approximately 3% of the mass M of the marine mammal in kilograms. Therefore, the volume V_0 at the surface in cubic meters (note 0.001 m^3/l) is $V_0 = 0.001 \times 0.03\, M$. The volume at depth z in meters is determined from the ratio of pressures. For salt water, this variation can be expressed approximately: $V(z) = V_0 \times 10 / (z+10)$. The radius A of an equivalent-volume spherical bubble is thus $A(z) = [V(z) / (4\pi/3)]^{1/3}$. Finally, the oscillation period for a spherical bubble is given by

$$T_{osc} = 97.1\frac{A}{\sqrt{P}},$$

where $P = 1.013 \times 10^5\,(1 + z/10)$ is the absolute pressure in Pascals at depth z. The calculation for impulse is carried out according to:

$$I = p_0 t_0 (1 - e^{-\Delta t / t_0}),$$

where Δt is T_s for calculating impulse levels for fishes. For marine mammals, Δt should be set to the minimum of T_s and T_{osc} (Goertner 1982).

4.3.6 Root-Mean-Square Levels

The rms sound level metric has gained popularity because it gives the most representative measure of the average effective amplitude over a transient signal's duration. This metric is especially well suited to characterizing sonar pings and signals such as windowed sine pulses. It also is quite widely applied for estimating impacts of impulsive airgun noise on marine mammals.

The rms metric is computed as the square root of the mean squared pressure over the signals "duration," the definition of which is somewhat ambiguous. Greene (1998) proposed a method that uses the interval between the times at which 5% and 95% of the total EFD is received. This method has been augmented (MacGillivray et al. 2002, 2003) to remove contributions from background noise when the signal to noise ratio is small. The method is applied by first determining the mean-square background noise amplitude σ^2, from which a noise-corrected cumulative energy density function is computed:

$$E_{\text{cum}}(T) = \int_0^T \left[p^2(t) - \sigma^2\right] dt \, .$$

The cumulative energy density function normally appears as the curve shown in the lower pane in **Figure 4.4**. If the background noise level is matched properly, then the sections of the cumulative EFD function will be constant prior to and after the primary transient pulse arrivals. The signal duration interval is still determined by the times at which the function crosses the 5% and 95% total EFD levels. The horizontal dashed lines in **Figure 4.4** represent the 5% and 95% levels, and the vertical lines represent corresponding start and stop times.

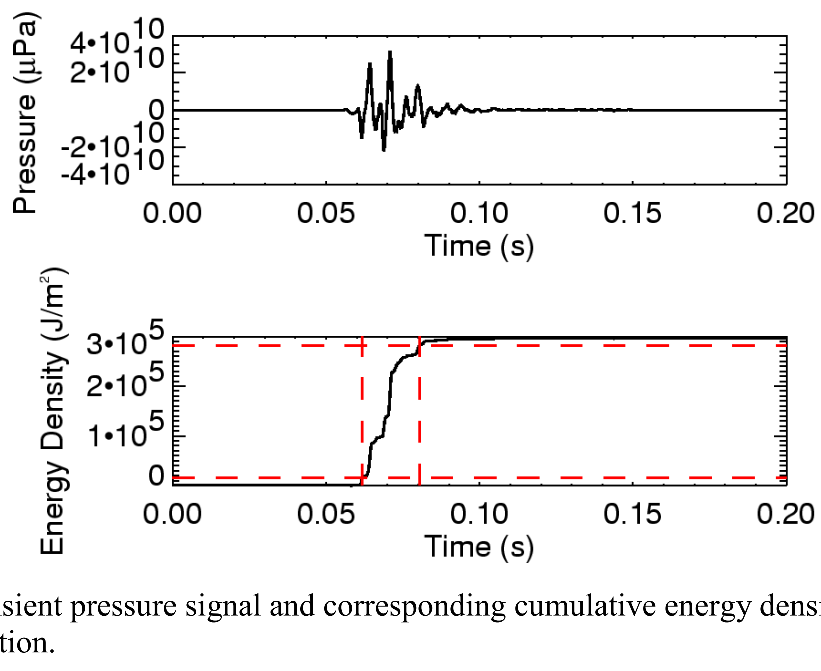

Figure 4.4. Transient pressure signal and corresponding cumulative energy density function.

The rms pressure then is computed from the difference between the 95% and 5% cumulative EFD, divided by the corresponding time difference:

$$p_{\text{rms}} = \sqrt{\frac{E(t_{95\%}) - E(t_{5\%})}{t_{95\%} - t_{5\%}}}$$

4.4 Data Gaps and Recommended Areas of Future Research

The understanding of the physical principles of underwater detonations and of the propagation of shock and sonic waves in the surrounding medium is in itself quite well developed and has been thoroughly formalized since decades ago (see Cole 1948). There are, however, significant gaps in the application of this formal knowledge in a meaningful way to the real life situations of offshore structures removal. The containment effect provided by setting the structure-cutting charges below a minimum prescribed depth of sediment has not been documented for a comprehensive range of seafloor consistencies, with the result that the extent of the transmission of explosive energy into the water column may be significantly greater than expected (Nedwell et al. 2001). Much of what is known from experience regarding underwater detonations within the seafloor comes from rock demolition blasting, which by its very nature is performed in an altogether different medium from the relatively compliant upper layers of sediment in which structure-cutting charges are deployed.

The methods for computing sound level metrics are well established. From the standpoint of providing a reliable physical evaluation of the injury potential to marine life from an underwater explosion, however, their applicability for gauging species-dependent impact suffers from a lack of standardization. It is often the case that damage thresholds such as TTS (recoverable hearing loss) for a particular class of animals are quoted as a decibel value with no specific indication of the type of metric, and thus the acoustic signal properties, to which that value pertains. A metric such as dB_{ht}(Species), which may indeed provide the most accurate evaluation of the sub-injury impact of an acoustic disturbance on a given marine life form, is currently limited in usefulness and reliability by the lack of a comprehensive database of audiograms based on measurements performed on a significant number of individuals per species.

A systematic research effort should be undertaken to model numerically the blast propagation for a range of charge sizes consistent with structure removal practices through a wide variety of sediment types and for different deployment depths below the sediment surface. Such modeling should extend to the transfer of energy into the water column both from the shock wave propagating through the interface, and later decaying into an acoustic signal, and from the oscillating bubble of detonation gases when breakout into the water does take place. Experimental validation of model results at every possible opportunity should form an integral part of the study; this requires accurate measurement of acoustic levels, and preferably full waveform recording, at one or more locations in the water columns as well as characterization of the sediment firmness near the structures being removed, which could be done by penetrometer probing or similar techniques. Once a reliable modeling approach has been generated and validated, forecasting of the acoustic levels distribution for planned operations would become possible from the type and location of the charge to be exploded, the depth of the water column, and the measured properties of the sediment in which the detonation occurs. In fact, by using a combined blast and acoustic modeling approach, the longer-range propagation of the sound energy from a cutting charge detonation could be accurately forecast given knowledge of the bottom topography and the sound velocity profile in the water. This would alert to possible areas of sound energy concentration that would be missed by simpler estimators, and would permit the establishment of more appropriate safe ranges or the iterative revision of the planned blast configuration to mitigate its effects. In combination with improved estimation of impact thresholds based on appropriate and standardized sound metrics, such a modeling-based assessment of each planned decommissioning operation involving explosive removal of underwater structures would provide the best ability to minimize its repercussions on the marine life environment.

CHAPTER 5
AFFECTED ENVIRONMENT

The following discussion of affected environment considers those components of the biological environment that are at the greatest risk of impact from explosive platform removal – marine fishes, marine turtles, and marine mammals. In the development of this text, emphasis has been placed on the presence and characteristics of species present in U.S. waters. Particular emphasis has been placed on listed and/or protected species – those protected under ESA and MMPA, respectively.

5.1 Marine Fishes

In two OCS Planning Areas, Gulf of Mexico and Pacific, large numbers of fishes associate with oil and gas structures. These fishes are briefly characterized below with emphasis on federally managed species.

5.1.1 Gulf of Mexico OCS Region

Offshore oil and gas structures of the northern Gulf of Mexico represent a significant albeit artificial habitat for pelagic and demersal fishes of the region. Platforms provide shelter and settlement sites for numerous species of reef and pelagic fishes. Nearly 4,000 platforms and other oil and gas structures on Louisiana's continental shelf represent a significant proportion of available hard bottom habitat for fishes with an affinity for structure.

Reef and pelagic fishes that associate with oil and gas platforms are broadly classified into coastal, offshore, and bluewater assemblages. Coastal platforms are in water depths of about 30 m or less and are characterized by variable conditions of limited water clarity. The offshore platform assemblage is in water depths ranging from 30 to 60 m, and bluewater platforms lie along the outer margin of the continental shelf in water depths of 60 m or more. Reef fishes such as snappers, groupers, grunts, porgies, squirrelfishes, angelfishes, damselfishes, butterflyfishes, and wrasses inhabit offshore and bluewater structures. Many of these reef fishes are managed by the Gulf of Mexico Fishery Management Council as part of a snapper-grouper (reef fish) management complex consisting of 73 species. Red snapper (*Lutjanus campechanus*) is the most important species economically of this group that regularly inhabits offshore oil and gas structures (Wilson and Nieland 2001). Reef fishes, including federally managed species, known to inhabit oil and gas platforms are listed in **Table 5.1**.

Most fishes associated with platforms in the Gulf of Mexico tend to remain relatively near or under the structures (Continental Shelf Associates, Inc. 1982; Gallaway and Lewbel 1982; Putt 1982). Stationary hydroacoustic surveys indicate that fish densities around platforms sampled with hydroacoustics are highest within a horizontal distance of 18 to 50 m from the structure (Stanley and Wilson 1998, 2002). For

Table 5.1

Reef Fishes That Associate with Oil and Gas Structures in the Gulf of Mexico
(Adapted from: Gallaway and Lewbel 1982; Gulf of Mexico Fishery Management Council 1998)

Family	Scientific Name	Common Name
Serranidae	*Epinephelus nigritus**	warsaw grouper
	*Epinephelus niveatus**	snowy grouper
	*Mycteroperca interstitialis**	yellowmouth grouper
	*Mycteroperca microlepis**	gag
	*Mycteroperca phenax**	scamp
	Paranthias furcifer	creole-fish
Lutjanidae	*Lutjanus campechanus**	red snapper
	*Lutjanus griseus**	gray snapper
	*Lutjanus jocu**	dog snapper
	*Lutjanus mahogoni**	mahogany snapper
	*Lutjanus synagris**	lane snapper
	*Ocyurus chrysurus**	yellowtail snapper
	*Rhomboplites aurorubens**	vermilion snapper
Haemulidae	*Haemulon aurolineatum**	tomtate
Sparidae	*Archosargus probatocephalus**	sheepshead
Kyphosidae	*Kyphosus incisor*	yellow chub
	Kyphosus sectatrix	Bermuda chub
Ephippidae	*Chaetodipterus faber*	Atlantic spadefish
Chaetodontidae	*Chaetodon aya*	bank butterflyfish
	*Chaetodon ocellatus**	spotfin butterflyfish
	Chaetodon sedentarius	reef butterflyfish
Pomacanthidae	*Holacanthus bermudensis*	blue angelfish
Pomacentridae	*Abudefduf saxatilis*	sergeant major
	Chromis enchrysurus	yellowtail reeffish
	Stegastes variabilis	cocoa damselfish
Labridae	*Bodianus pulchellus*	spotfin hogfish
	*Bodianus rufus**	Spanish hogfish
	Halichoeres bivittatus	slippery dick
	*Lachnolaimus maximus**	hogfish
	Thalassoma bifasciatum	bluehead
Blenniidae	*Hypsoblennius hentzi*	feather blenny
	Hypsoblennius invemar	tessellated blenny
	Ophioblennius atlanticus	redlip blenny
	Parablennius marmoreus	seaweed blenny
	Scartella cristata	molly miller
Sphyraenidae	*Sphyraena barracuda*	great barracuda
Balistidae	*Balistes capriscus**	gray triggerfish

* Managed species.

platforms in shelf waters, densities of fishes within the zone of influence of the platform were fairly uniform with respect to water depth, whereas in slope waters most of the fishes were concentrated above 60 m (Stanley and Wilson 1998). Smaller site-attached reef fishes vertically partition the habitat created on platform legs. Blennies utilize as living areas empty barnacle shells and interstitial spaces created by the epibiota attached to platform legs (Gallaway and Lewbel 1982). Damselfishes, wrasses, and others closely associate with legs and cross-members and pilings that support the platforms (Gallaway and Lewbel 1982; Boland 2002). Larger reef-associated species such as chubs, snappers, triggerfishes, angelfishes, butterflyfishes, spadefishes, and sheepshead are found throughout the water column and prefer the cover provided by the structure.

The common pelagic fish assemblage found in shelf waters of the Gulf of Mexico is usually termed coastal pelagic. Major coastal pelagic families occurring in the Gulf are requiem sharks, ladyfish, anchovies, herrings, mackerels, jacks, mullets, bluefish, and cobia. Coastal pelagic species traverse shelf waters of the region throughout the year. Some species form large schools (e.g., Spanish mackerel), while others travel singly or in smaller groups (e.g., cobia). The distribution of most species depends upon water column structure, which varies spatially and seasonally. Many coastal pelagic species associate with oil and gas structures in the northern Gulf of Mexico.

A unique aspect of oil and gas structures when compared with natural hard bottom is the vertical component that extends throughout the water column (Stanley and Wilson 2002). Adults and early stages of coastal pelagic species are attracted to the upper portions of these structures. Jacks (Carangidae) exemplify this phenomenon. Large schools of blue runner, crevalle jacks, lookdown, Atlantic bumper, and Atlantic moonfish occur in the upper portion of the water column around offshore platforms (Gallaway and Lewbel 1982). Other pelagic species including bluefish, king and Spanish mackerels, little tunny, and other tunas also associate with platforms. Coastal pelagic fishes including federally managed species, commonly found around platforms, are given in **Table 5.2**.

Epipelagic or highly migratory species such as billfishes, dolphin, tunas, and wahoo are found around blue water platforms. Little is known about the spatial relationships that these species have with offshore structures, but these structures seem to have a fish attraction device (FAD) effect (Edwards et al. 2002). Highly migratory species including sharks also are managed by the NMFS.

5.1.2 Pacific OCS Region

Managed fishes in the Pacific OCS region that associate with offshore oil and gas structures are classified as groundfishes. The groundfish management unit includes over 70 species, most of which are rockfishes (Scorpaenidae).

Table 5.2

Pelagic Species That Associate with Oil and Gas Structures in the Gulf of Mexico (Adapted from: Gallaway and Lewbel 1982; Gulf of Mexico Fishery Management Council 1998)

Family	Scientific Name	Common Name
Pomatomidae	*Pomatomus saltatrix*	bluefish
Rachycentridae	*Rachycentron canadum**	cobia
Carangidae	*Caranx crysos*	blue runner
	Caranx hippos	crevalle jack
	Caranx latus	horse-eye jack
	Chloroscombrus chrysurus	Atlantic bumper
	Decapterus punctatus	round scad
	Elagatis bipinnulata	rainbow runner
	Selene setapinnis	Atlantic moonfish
	Selene vomer	lookdown
	Seriola dumerili	greater amberjack
	Seriola fasciata	lesser amberjack
	Seriola rivoliana	almaco jack
Coryphaenidae	*Coryphaena hippurus**	dolphin
Istiophoridae	*Istiophorus platypterus**	sailfish
	*Makaira nigricans**	blue marlin
Scombridae	*Acanthocybium solanderi*	wahoo
	*Euthynnus alletteratus**	little tunny
	*Katsuwonus pelamis**	skipjack tuna
	Scomber japonicus	chub mackerel
	*Scomberomorus cavalla**	king mackerel
	*Scomberomorus maculatus**	Spanish mackerel
	*Thunnus albacares**	yellowfin tuna
	*Thunnus atlanticus**	blackfin tuna

* Managed species.

Assemblages of fishes associated with platforms in the Santa Barbara Channel have been recently studied by Love et al. (2000). These platforms lie in water depths ranging from 49 to 224 m. Assemblages are composed of 15 families, with rockfishes (*Sebastes* spp.) contributing most of the species, followed by greenlings (hexagrammids) and surf perches (embiotocids). Species and families associated with platforms in the Santa Barbara Channel are provided in **Table 5.3**.

Table 5.3

Fish Species Associated with Oil and Gas Platforms in Santa Barbara Channel
(From: Love et al. 2001)

Family	Scientific Name	Common Name
Scorpaenidae	*Sebastes aleutianus**	rougheye rockfish
	*Sebastes atrovirens**	kelp rockfish
	*Sebastes auriculatus**	brown rockfish
	*Sebastes babcocki**	redbanded rockfish
	*Sebastes carnatus**	gopher rockfish
	*Sebastes caurinus**	copper rockfish
	*Sebastes chlorostictus**	greenspotted rockfish
	Sebastes constellatus	starry rockfish
	*Sebastes dallii**	calico rockfish
	*Sebastes elongates**	greenstriped rockfish
	Sebastes ensifer	swordspine rockfish
	*Sebastes entomelas**	widow rockfish
	*Sebastes flavidus**	yellowtail rockfish
	*Sebastes goodei**	chilipepper
	*Sebastes helvomaculatus**	rosethorn rockfish
	*Sebastes hopkinsi**	squarespot rockfish
	*Sebastes jordani**	shortbelly rockfish
	*Sebastes levis**	cowcod
	*Sebastes macdonaldi**	Mexican rockfish
	*Sebastes miniatus**	vermilion rockfish
	Sebastes moseri	whitespeckled rockfish
	*Sebastes mystinus**	blue rockfish
	*Sebastes paucispinis**	bocaccio
	*Sebastes pinniger**	canary rockfish
	*Sebastes rosaceus**	rosy rockfish
	*Sebastes rosenblatti**	greenblotched rockfish
	*Sebastes ruberrimus**	yelloweye rockfish
	*Sebastes rubrivinctus**	flag rockfish
	*Sebastes rufus**	bank rockfish
	*Sebastes saxicola**	stripetail rockfish
	Sebastes semicinctus	halfbanded rockfish
	*Sebastes serriceps**	tree rockfish
	Sebastes simulator	pinkrose rockfish
	*Sebastes umbrosus**	honeycomb rockfish
	Sebastes wilsoni	pygmy rockfish
	*Sebastes zacentrus**	sharpchin rockfish
	Sebastomus	Sebastomus group
	Scorpaena guttata	spotted scorpionfish

Table 5.3. Fish Species Associated with Oil and Gas Platforms in Santa Barbara Channel (From: Love et al. 2001). (continued).

Family	Scientific Name	Common Name
Hexagrammidae	*Hexagrammos decagrammos**	kelp greenling
	*Ophiodon elongatus**	lingcod
	Oxylebius pictus	painted greenling
	Zaniolepis sp.	combfish
	Zaniolepis frenata	unid. shortspine combfish
	Zaniolepis latipinnis	longspine combfish
Pomacentridae	*Chromis punctipinnis*	blacksmith
	Hypsypops rubicundus	garibaldi
Embiotocidae	*Damalichthys vacca*	pile perch
	Embiotocidae sp.	unid. surfperch
	Phanerodon atripes	sharpnose surfperch
	Rhacocilus toxotes	rubberlip surfperch
	Zalembius rosaceus	pink surfperch
Merlucciidae	*Merluccius productus**	Pacific hake
Flatfish	*Microstomus pacificus**	Dover sole
Gobiidae	*Coryphopterus nicholsi*	blackeye goby
Cottidae	*Scorpaenichthys marmoratus*	cabezon
Kyphosidae	*Girella nigricans*	opaleye
	Medialuna californiensis	halfmoon
Serranidae	*Paralabrax clathratus*	kelp bass
Labridae	*Semicossyphus pulcher*	sheephead
Anarrhichadidae	*Anarrhichthys ocellatus*	wolf-eel
Bathymasteridae	*Bathymasteridae* sp.	ronquils
Chimaeridae	*Hydrolagus colliei**	ratfish
Clupeidae	*Sardinops sagax*	Pacific sardine

* Managed species.

Fishes from 15 families and over 60 species colonize platforms in Santa Barbara Channel (Love et al. 1994, 1999, 2000, 2001). Platform assemblages are dominated in terms of biomass and numbers by rockfishes (*Sebastes* spp.). Twenty-nine species inhabit bottom and mid-waters around the platforms. The most common species in bottom waters around the platforms are halfbanded rockfish (*Sebastes semicinctus*), greenspotted rockfish (*Sebastes chlorostictus*), copper rockfish (*Sebastes caurinus*), and vermilion rockfish (*Sebastes miniatus*). In mid-water, widow rockfish (*Sebastes entomelas*), juvenile rockfishes (*Sebastes* spp.), and blacksmith (*Chromis punctipinnis*) were most common. Rockfish juveniles (less than 2 years old) were most numerous in mid-water, where rockfish larger than 18 cm were rarely observed. In bottom waters, larger adults and subadults were abundant. The bottom area of the platforms consistently supported more species than mid-water areas likely because of greater habitat complexity in bottom waters.

5.1.3 Alaska OCS Region

In the Alaska OCS, there is no information on platform-associated fishes for the primary offshore oil and gas field – Cook Inlet. There are platforms and structures in the Beaufort Sea, but these are built upon large gravel causeways or berms and will not be removed with explosives. Although the platform fauna of the Alaska region have not been characterized as they have been in the Gulf of Mexico and Santa Barbara Channel, Cook Inlet is a much smaller water body that supports important fisheries, particularly salmon and Pacific herring. Economically important species managed by the North Pacific Fishery Management Council are Pacific herring, salmon, and groundfishes (**Table 5.4**). Ichthyofaunal surveys conducted in the Gulf of Alaska and Cook Inlet revealed the spatial and temporal dynamics of fishes inhabiting the area (Blackburn et al. 1979; Mecklenburg et al. 2002; Mueter and Norcross 2002).

Spatial and temporal fluctuations in size composition and distribution of pelagic and demersal species is a common pattern in Cook Inlet. Most of the common species move out of nearshore areas in the late summer and fall and remain offshore until spring. Small pelagic species including Pacific herring, capelin, long fin, and surf smelts are among those species that migrate out of the shallows in fall. These species are an important food source for larger predators such as salmon, sea birds, and marine mammals.

Table 5.4

Managed Fish Species Found in Lower Cook Inlet, Alaska (From: North Pacific Fishery Management Council 2002)

Family	Scientific Name	Common Name
Clupeidae	*Clupea pallasii*	Pacific herring
Salmonidae	*Oncorhynchus gorbuscha*	pink salmon
	Oncorhynchus keta	chum salmon
	Oncorhynchus kisutch	coho salmon
	Oncorhynchus nerka	sockeye salmon
	Oncorhynchus tshawytscha	Chinook salmon
Gadidae	*Gadus macrocephalus*	Pacific cod
	Theragra chalcogramma	walleye pollock
Scorpaenidae	*Sebastolobus altivelis*	longspine thornyhead
	Sebastes caurinus	copper rockfish
	Sebastes helvomaculatus	rosethorn rockfish
	Sebastes maliger	quillback rockfish
	Sebastes nebulosus	China rockfish
	Sebastes nigrocinctus	tiger rockfish
	Sebastes pinniger	canary rockfish
	Sebastes ruberrimus	yelloweye rockfish
Anoplopomatidae	*Anoplopoma fimbria*	sablefish
Hexagrammidae	*Pleurogrammus monopterygius*	Atka mackerel

Table 5.4. Managed Fish Species Found in Lower Cook Inlet, Alaska (From: North Pacific Fishery Management Council 2002). (continued).

Family	Scientific Name	Common Name
Pleuronectidae	*Atheresthes stomias*	arrowtooth flounder
	Hippoglossus stenolepis	Pacific halibut
	Hippoglossoides elassodon	flathead sole
	Hippoglossoides robustus	Bering flounder
	Psettichthys melanostictus	sand sole
	Isopsetta isolepis	butter sole
	Lepidopsetta bilineata	southern rock sole
	Lepidopsetta polyxystra	northern rock sole
	Limanda aspera	yellowfin sole
	Limanda proboscidea	longhead dab
	Parophrys vetulus	English sole
	Platichthys stellatus	starry flounder
	Pleuronectes quadrituberculatus	Alaska plaice

The salmonids are the primary large pelagic fishes in the area. These species enter the shallows in spring and migrate up adjacent rivers during summer months to spawn. Young salmon migrate downstream during summer months to rich estuarine feeding grounds.

Demersal species found in Cook Inlet are cod, flatfishes, sculpins, greenlings, and rockfishes. These species will move into shallower water during spring and summer. Rockfishes, greenlings, sculpins, and rock sole prefer structured rocky habitats. Juvenile salmon, herring, and sand lance will associate with rocky areas during summer months. Pacific halibut are found on rubble or shell hash bottom types. Other flatfishes are most common on soft sedimentary substrates.

5.2 Marine Turtles

5.2.1 Marine Turtles of North America

Currently, all marine turtles are placed within one order, Chelonii, and two families, Cheloniidae and Dermochelyidae. Cheloniids possess a fused, hard shell that is covered with horny scutes of variable number. Dermochelyids possess a shell characterized by extreme reduction of bones in both carapace and plastron (upper and lower shell, respectively), whose epithecal layer consists of a mosaic of thousands of small, polygonal bones supported by a thick matrix of oil-laden, cartilagenous dermal tissue (Marquez 1990).

Marine turtle sexes are dimorphic in both families. Female marine turtles typically come ashore on sandy beach and dune habitats only to nest, while males remain permanently aquatic (Wyneken 1997). All species exhibit stereotyped nesting behavior, lay relatively large numbers of eggs several times during the reproductive period, and demonstrate relatively strong attachment to a particular location for nesting (with inter- and intraspecific variability) (Miller 1997).

Cheloniid marine turtles have a pantropical distribution, with periodic migrations into temperate habitats for opportunistic feeding during warm seasons (Marquez 1990). In North American waters, there are six species within four genera: *Caretta, Chelonia, Eretmochelys,* and *Lepidochelys.* The family Dermochelyidae is represented by one genus, *Dermochelys*. Brief descriptions of marine turtle species that may occur within North American waters are found below.

Loggerhead Turtle

The loggerhead turtle, *Caretta caretta,* is the largest cheloniid turtle, with a carapace length of approximately 81 to 105 cm. Mature individuals weigh about 135 kg, though some individuals may attain much larger sizes (Marquez 1990; Ernst et al. 1994). Loggerhead turtles are widely distributed in coastal tropical and subtropical waters, and are also commonly found in temperate waters, moving within the bounds of warm currents (e.g., Gulf Stream, North Equatorial Current, Kuroshio Current, and California Current in the northern hemisphere). Loggerhead turtles are widely distributed throughout their range, with respect to water depth. They are found in open ocean habitats, waters of the continental shelf, and nearshore and coastal areas such as bays, lagoons, salt marshes, creeks, and the mouths of large rivers (Ernst et al. 1994). The loggerhead turtle is omnivorous, though benthic invertebrates appear to be the most important constituents of their diet.

Though not commercially exploited for its flesh or shell, *Caretta* nesting populations are declining as a result of incidental catch in shrimp trawls in both southern Queensland, Australia and in the U.S. north of Cape Canaveral. The larger populations in Florida south of Cape Canaveral and the relatively small population off South Africa are increasing (Pritchard 1997). *Caretta* is currently listed as threatened in U.S. waters under ESA.

Green Turtle and Black Turtle

The green turtle, *Chelonia mydas*, ranges from approximately 81 to 112 cm in carapace length. It is widely distributed in tropical and subtropical waters, and migrates across the open ocean to feeding habitats in shallow water supporting an abundance of submerged vegetation (Ernst et al. 1994).

The black turtle, *Chelonia agassizii*, is approximately 70 to 80 cm in carapace length (Marquez 1990). It inhabits primarily coastal waters along the west coast of America, primarily between Baja California to southern Peru. This species is not commonly observed in the open ocean environment.

Chelonia, in adulthood, are primarily herbivorous. Food items include algae, red mangrove (*Rhizophora* spp.) roots and leaves, and seagrasses. Feeding behavior in early stages (hatchling to juvenile) is assumed to be carnivorous (Marquez 1990; Ernst et al. 1994).

The green turtle has long been harvested for both meat and eggs under increasing demand for subsistence and local markets by indigenous people. However, local colonies appear to be on the increase, and on the whole the species does not appear to be faced with imminent extinction (Pritchard 1997). Florida nesting populations of green turtles are currently listed as endangered under the ESA, while other nesting populations in U.S. waters are listed as threatened. The black turtle is captured in uncontrolled numbers within areas of their range. Consequently, the outlook for this species is, in the long run, uncertain.

Hawksbill Turtle

The average carapace length in adult female hawksbill turtles (*Eretmochelys imbricata*) ranges from approximately 50 to 114 cm. This species is predominantly tropical and distributed throughout the central Atlantic and Pacific regions of America. It is characteristically an inhabitant of tropical, exposed hard bottom habitats, including coral reefs. It also may be found in shallow coastal areas such as mangrove-bordered embayments, estuarine habitats, mud-bottomed lagoons, and creeks and passes (Ernst et al. 1994). Capture/recapture data for subadult hawksbills suggest that at least part of the population demonstrates residential, or non-migratory, behavior, though these adults may perform migratory movements during the breeding season. The hawkbill turtle is principally carnivorous, and its diet consists primarily of sponges. In addition, it is known to eat coelenterates, ascideans, bryozoans, echinoids, mollusks, barnacles, crustaceans, algae, seagrasses, and mangrove (*Rhizophora*).

Intense commercial trade of hawksbill turtle shell (or “carey”) has led to widespread concerns that this species is being seriously overexploited (Pritchard 1997; Fleming 2001). The future of this species has been labeled “indeterminate.” The hawksbill turtle is currently listed as endangered under ESA (Pritchard 1997).

Kemp's Ridley and Pacific (Olive) Ridley

The Kemp's ridley, *Lepidochelys kempii*, ranges from approximately 52 to 75 cm in carapace length. Adult Kemp's ridleys usually occur only in the Gulf of Mexico, though juveniles and subadults may range between tropical and temperate waters of the northwestern Atlantic Ocean and occasionally Europe and Africa. In the Gulf of Mexico, Kemp's ridleys usually inhabit sandy and muddy bottom habitats, including bays, coastal lagoons, and river mouths.

The Pacific (or olive) ridley, *Lepidochelys olivacea*, is similar in size, but has a slightly deeper body than the Kemp's ridley (Marquez 1990; Ernst et al. 1994). It is pantropical, though occurs primarily within the northern hemisphere, with the 20°C isotherms as its distributional boundaries. Adults are most frequently observed in shallow waters, though there are observations of them feeding in deeper waters (i.e., to 200 m) (Marquez 1990; Ernst et al. 1994).

Lepidochelys are carnivorous throughout their life cycles, feeding principally on crabs, shrimps, mollusks, echinoids, jellyfishes, and fishes (Marquez 1990; Ernst et al. 1994).

Lepidochelys are listed as endangered under ESA. The Kemp's ridley is considered the rarest extant marine turtle species, although there are current apparent population increases (Pritchard 1997). The Pacific ridley, in contrast, remains the most numerous species of marine turtle. Nesting sites are reasonably protected, though incidental take by trawlers is significant in certain areas (Pritchard 1997).

Leatherback Turtle

The leatherback turtle, *Dermochelys coriacea*, is among the world's largest living reptiles. Carapace lengths range from approximately 130 to 260 cm. They are easily recognized by their large size and leathery, keeled shell. The leatherback turtle possesses unique abilities when compared to other marine turtles. They maintain limited endothermic (i.e., warm blooded) ability, due to the insulative and thermogenic qualities of their thick layers of oil-saturated, subepidermal fat; large, insulating body mass; and a countercurrent heat exchange system of arteries and veins in their limbs (Ernst et al. 1994; Ruckdeschel et al. 2000). In addition, the leatherback turtle is physiologically capable of repeatedly diving to and foraging at depths of over 1,000 m.

Though mainly tropical nesters, the leatherback turtle forages in all waters poleward to the Arctic and Antarctic (Marquez 1990). They feed extensively on pelagic, gelatinous, and other soft-bodied invertebrates, primarily jellyfishes and salps. Data suggest their distribution is strongly influenced by mesoscale and local oceanographic features that concentrate their prey items. They forage within deep scattering layers of the open ocean, but are also commonly seen relatively close to shore because of their prey distribution (Ruckdeschel et al. 2000).

Adult leatherback turtles are not exploited commercially, though subsistence take of eggs, and sometimes of nesting adults, has been intense. Atlantic colonies, on the whole, appear to be reasonably secure and in some cases increasing. However, serious declines have been documented in Pacific Mexico and Costa Rica (Pritchard 1997). The leatherback turtle is currently listed as endangered in U.S. waters under ESA.

5.2.2 Distributions of Marine Turtles and Their Association with Offshore Oil and Gas Structures

There are differential distributions among the various sea turtle life stages – hatchling, juvenile, and adult (Marquez 1990; Hirth 1997; Musick and Limpus 1997). For example, in the Gulf of Mexico, hatchling turtles are typically pelagic and may be found within zones of water mass convergence and/or sargassum rafts, which are rich in prey and provide shelter (NMFS and USFWS 1991; Hirth 1997). These hatchlings may have originated from nesting sites along Gulf of Mexico shores or adjacent areas such as the Caribbean Sea. Juvenile turtles may actively move across the open Gulf to shallow water developmental habitats and adult foraging habitats, respectively. Adult foraging habitats may be, in some species or populations, geographically distinct from their juvenile developmental habitats (Musick and Limpus 1997). All marine turtles migrate, at least short distances, from foraging areas to mating areas. After mating, males, which remain permanently aquatic, return to foraging areas, and females move to nesting areas. After a reproductive period of up to several months, females return to foraging areas (Miller 1997).

Most marine turtle species commonly inhabit areas characterized by topographic relief such as exposed rock features and reefs (Carr 1954; Booth and Peters 1972; Stoneburner 1982; Witzell 1982). Offshore oil and gas structures also provide topographic relief in areas and have been shown to attract marine turtles (Fuller and Tappan 1986; Rosman et al. 1987; Gitschlag and Renaud 1989; Lohoefener et al. 1989; Gitschlag 1990; Lohoefener et al. 1990; Gitschlag and Herczeg 1994). Turtles may use offshore platforms as places to feed and rest, and as a refuge from predators and strong currents (NRC 1996).

Observational data from the Gulf of Mexico indicate that the loggerhead turtle is the most common marine turtle species sighted near offshore oil and gas structures, though green turtles, hawksbill turtles, Kemp's ridley, and leatherback turtles also have been sighted. These data also indicate that certain individual loggerheads may reside at specific offshore structures for extended periods of time (Rosman et al. 1987; Gitschlag and Renaud 1989).

5.2.3 Distributions of Marine Turtle Species Within MMS OCS Planning Areas

The distributions of marine turtle species within MMS OCS Planning Areas where there are offshore oil and gas structures (Gulf of Mexico, Pacific, and Alaska OCS Planning Areas) are listed in **Table 5.5**.

Table 5.5

Marine Turtle Species Within Minerals Management Service Gulf of Mexico (GOM), Pacific, and Alaska Outer Continental Shelf (OCS) Planning Areas (Derived from Pritchard 1990)

Common Name	Genus/Species	GOM OCS	Pacific OCS	Alaska OCS
Loggerhead turtle	*Caretta caretta*	X[1]	X[2]	X[2]
Green turtle	*Chelonia mydas*	X[1]		
Black turtle	*Chelonia agassizii*		X[2]	
Hawksbill turtle	*Eretmochelys imbricata*	X[2]		
Kemp's ridley	*Lepidochelys kempii*	X[1]		
Pacific (olive) ridley	*Lepidochelys olivacea*		X[1]	
Leatherback turtle	*Dermochelys coriacea*	X[1]	X[1]	X[1]

[1] Normal distributional range.
[2] Occurrence seasonal or extralimital.

5.3 Marine Mammals

The following summary of marine mammals has been organized by OCS region – Gulf of Mexico, Pacific, and Alaska. Marine mammal data have been compiled and summarized based on both historical and recent aerial and/or shipboard surveys. Focus has been placed on those areas within each region where oil and gas platforms or other OCS facilities have been placed and will require removal.

All marine mammals are protected by federal law (MMPA), which affords individuals and populations from mortality, injury, or harassment. Under MMPA, a species may be designated as a **depleted** or **strategic** stock. A stock is depleted when declines in numbers result in the population falling below its optimal sustainable population. A stock is considered strategic when it is presumed that human activities may be having a deleterious effect on the population and that the population may not be sustainable. In addition, individual species may also be designated as threatened or endangered under the ESA. A stock may be classified as threatened or endangered, depleted, and strategic simultaneously. Systematic conventions follow those outlined by Rice (1998).

5.3.1 Gulf of Mexico OCS Region

Toothed whales are the by far the most abundant marine mammal in the Gulf of Mexico (**Table 5.6**). Seals and sea lions are absent, and Bryde's whale is the only mysticete that is seen with any regularity (Davis et al. 2000; Würsig et al. 2000). Sixteen species are routinely sighted in the Gulf of Mexico, and most are year-round residents (Davis et al. 2000). Manatees are typically sighted off the coast of Florida but also have been observed off the coast of Texas, Louisiana, and/or Mississippi virtually every summer since 1970 (Würsig et al. 2000). As noted previously, it is extremely unlikely that manatees will be adversely affected by explosive platform removal activities over the continental shelf or slope.

Bottlenose dolphins and Atlantic spotted dolphins are by far the dominant species of the continental shelf and shelf edge. Bottlenose dolphins can also range onto the continental slope in the northeast Gulf. The most abundant species in deepwater are *Stenella* spp. dolphins. Bryde's whales have been found in the northeastern Gulf along the 100-m contour.

The deepwater species appear to have geographical preferences (Davis et al. 2000; Würsig et al. 2000):

- Pygmy and dwarf sperm whales, killer whales, pantropical spotted dolphins, striped dolphins, and Risso's dolphins range throughout the northern Gulf; however, pantropical spotted and striped dolphins may be rare in the northwest Gulf. Killer whales tend to concentrate near the Mississippi delta.

Table 5.6

Abundance, Protective Status (Under the Endangered Species Act), Habitat Characteristics, Group Size, and Dive Characteristics of Marine Mammals That are Known to (or May) Occur in the Northern Gulf of Mexico. The Number of Xs Indicates the Relative Occurrence of the Species in the Continental Shelf, Slope, and Offshore Area (Increasing Number of Xs Indicate an Increase in Occurrence)

Species	Occurrence[1]	Abundance[2]	Density[3] [#/100 km^2] (CV)	g(0)[4]	ESA Status[5]	Habitat	Continental Shelf		Slope	Offshore Waters	Season[1]	Group Size[6]	Dive Duration	
							Nearshore	Offshore					Average	Range (min)
Odontocetes														
Sperm whale (*Physeter macrocephalus*)	Common	530	0.111 (0.41)	0.87	E	Slope and deep sea			X	X	All Year	1-50 (2)	Long	30-120
Pygmy sperm whale (*Kogia breviceps*)	Common	733[a]	0.968 (0.47)	0.19		Slope and deep sea			XX	X	All Year	1-6 (2)	Long	
Dwarf sperm whale (*Kogia sima*)	Common	733[a]	0.968 (0.47)	0.19		Shelf edge and slope		X	XX	X	All Year	1-10 (2)	Long	
Cuvier's beaked whale (*Ziphius cavirostris*)	Rare	159	0.308 (0.76)	0.13		Pelagic			XX	X	All Year	1-25	Long	20-40
Sowerby's beaked whale (*Mesoplodon bidens*)	Extralimital	150[b]	N.A.	0.26		Pelagic			XX	X	?	1-10	Long	>28
Gervais' beaked whale (*Mesoplodon europaeus*)	Uncommon	150[b]	N.A.	0.26		Pelagic			XX	X	?	2-5	Long	
Blainville's beaked whale (*Mesoplodon densirostris*)	Rare	150[b]	N.A.	0.26		Pelagic			XX	X	?	1-12	Long	45
Rough-toothed dolphin (*Steno bredanensis*)	Common	852	0.114 (0.83)	1		Mostly pelagic			X	X	All Year	1-50 (34)	Short	15
Bottlenose dolphin (*Tursiops truncatus*)	Common	5,618[c]	1.358 (0.47)	0.561		Shelf waters	XXX	XXX	X	X	All Year	1-90 (7-9)	Short	12
Pantropical spotted dolphin (*Stenella attenuata*)	Common	46,625	11.687 (0.24)	1		Pelagic		X	XX	XXX	All Year	5-1000 (67)	Short	
Atlantic spotted dolphin (*Stenella frontalis*)	Common	3,213	0.235 (0.76)	0.561		Shelf waters	XX	X			All Year	1-85 (25-32)	Short	2
Spinner dolphin (*Stenella longirostris*)	Common	11,251	2.820 (0.60)	1		Coastal and pelagic		X	X	X	All Year	1-750 (63)	Short	
Clymene dolphin (*Stenella clymene*)	Common	10,093	2.530 (0.60)	1		Pelagic			X	X	All Year	2-200 (97)	Short	
Striped dolphin (*Stenella coeruleoalba*)	Common	4,858	1.098 (0.72)	1		Pelagic			X	X	All Year	10-500 (67)	Short	
Short-beaked common dolphin (*Delphinus delphis*)	Possible	N.A.	N.A.	0.561		Continental shelf and pelagic	X	X	X	X	?	10-500	Short	

Table 5.6. Abundance, Protective Status (Under the Endangered Species Act), Habitat Characteristics, Group Size, and Dive Characteristics of Marine Mammals That are Known to (or May) Occur in the Northern Gulf of Mexico. The Number of Xs Indicates the Relative Occurrence of the Species in the Continental Shelf, Slope, and Offshore Area (Increasing Number of Xs Indicate an Increase in Occurrence) (continued).

Species	Occurrence[1]	Abundance[2]	Density[3] [#/100 km^2] (CV)	g(0)[4]	ESA Status[5]	Habitat	Continental Shelf		Slope	Offshore Waters	Season[1]	Group Size[6]	Dive Duration	
							Nearshore	Offshore					Average	Range (min)
Long-beaked common dolphin (*Delphinus capensis*)	Possible	N.A.	N.A.	0.561		Coastal waters	X	X			?	10-500	Short	
Fraser's dolphin (*Lagenodelphis hosei*)	Common	127	0.067 (0.94)	1		Depth >1,000 m			X	XX	?	4-1000	Short	
Risso's dolphin (*Grampus griseus*)	Common	3,040	1.358 (0.40)	0.561		Depth 400-1,000 m		X	XX	X	All Year	1-250 (9)	Short	<30
Melon-headed whale (*Peponocephala electra*)	Common	3,965	0.435 (0.94)	1		Pelagic		X	XX	XX	?	30-500	Short	
Pygmy killer whale (*Feresa attenuata*)	Uncommon	518	0.078 (0.94)	0.561		Deep pelagic			X	X	All Year	1-50 (15)	Short	
False killer whale (*Pseudorca crassidens*)	Uncommon	817	0.365 (0.94)	0.561		Pelagic			X	X	?	20-100 (31)	Short	
Killer whale (*Orcinus orca*)	Uncommon	277	0.030 (0.83)	0.561		Coastal	X	X	X	X	?	1-50	Short	
Short-finned pilot whale (*Globicephala macrorhynchus*)	Common	1,471	0.369 (0.65)	1		Mostly pelagic			X	X	All Year	1-85 (33)	Short	15
Long-finned pilot whale (*Globicephala melas*)	Possible	N.A.	N.A.	1		Mostly pelagic			X	X	?	1-100	Short	
<u>*Mysticetes*</u>														
North Atlantic right whale (*Balaena glacialis*[d])	Extralimital	N.A.	N.A.	0.902	E	Coastal and shelf waters	XX	X			?	1-30	Short	
Humpback whale (*Megaptera novaeangliae*)	Rare	N.A.	N.A.	0.902	E	Nearshore and banks	XX	XX		X	?	1-15	Short	5-20
Minke whale (*Balaenoptera acutorostrata*)	Rare	N.A.	N.A.	0.84		Continental shelf, coastal waters	X	X			?	1-3	Short	
Bryde's whale (*Balaenoptera edeni*)	Uncommon	35	0.006 (0.94)	0.902		All	XX	X	X	X	All Year	1-7 (4)	Short	
Sei whale (*Balaenoptera borealis*)	Rare	N.A.	N.A.	0.902	E	All	X	X	X	X	?	1-5	Short	
Fin whale (*Balaenoptera physalus*)	Rare	N.A.	N.A.	0.902	E	All	X	X	X	X	?	1-7	Short	4-17
Blue whale (*Balaenoptera musculus*)	Extralimital	N.A.	N.A.	0.902	E	All	X	X	X	X	?	1-5	Short	5-15

Table 5.6. Abundance, Protective Status (Under the Endangered Species Act), Habitat Characteristics, Group Size, and Dive Characteristics of Marine Mammals That are Known to (or May) Occur in the Northern Gulf of Mexico. The Number of Xs Indicates the Relative Occurrence of the Species in the Continental Shelf, Slope, and Offshore Area (Increasing Number of Xs Indicate an Increase in Occurrence) (continued).

Species	Occurrence[1]	Abundance[2]	Density[3] [#/100 km²] (CV)	g(0)[4]	ESA Status[5]	Habitat	Continental Shelf		Slope	Offshore Waters	Season[1]	Group Size[6]	Dive Duration	
							Nearshore	Offshore					Average	Range (min)
<u>*Sirenian*</u>														
West Indian manatee (*Trichechus manatus*)	Common	1,856	N.A.		E	Very near shore	X				All Year			

[1] From Würsig et al. (2000).
[2] Abundance estimate from Davis et al. (2000) and Waring et al. (2001, 2002).
[3] Densities based on the 1996/97 GulfCet II surveys for the northern Gulf (Davis et al. 2000), cor rected for f(0) and g(0).
[4] g(0) is the probability of an animal being at the surface at any given time. g(0) depends on group size and is given for average group sizes seen in the Gulf of Mexico (if available); g(0) = 1 for group sizes >16.
[5] E = endangered.
[6] The range and (average) group size are shown.
[a] Estimate for dwarf and pygmy sperm whales.
[b] Estimate for all *Mesoplodon* spp.
[c] Gulf of Mexico continental shelf edge and continental slope stock.
[d] *Eubalaena* [=*Balaena*] per Rice (1998).

- False killer whales, pygmy killer whales, Fraser's dolphin, and beaked whales range throughout the northern Gulf, but are rare.
- Sperm whales generally occur along the lower continental shelf throughout the northern Gulf and may congregate at the 1,000-m isobath near the Mississippi River delta.
- Spinner dolphins occur in the north-central and northeast Gulf of Mexico.
- Short-finned pilot whales and melon-headed whales occur in the north-central and northwest Gulf.
- The distribution of rough toothed dolphins and clymene dolphins may vary from year to year, occurring either in the northeast or northwest Gulf.

There have been recent surveys of marine mammals in the Gulf of Mexico (Davis et al. 2000), and Würsig et al. (2000) have summarized current knowledge on the subject. Some of the data needed to plan monitoring and mitigation measures are summarized in **Table 5.6**. Caution needs to be used in interpreting and using these kinds of data. Bottlenose dolphins and Atlantic spotted dolphins appear to be the most common species on the continental shelf. However, environmental conditions could cause a normally pelagic offshore species to venture onto the continental shelf while following an abundance of potential food.

5.3.2 Pacific OCS Region

Numerous marine mammal species are resident or transitory throughout the Pacific OCS Region. This section deals only with marine mammals found in those areas where offshore platforms occur – offshore southern California (portions of the Southern California Bight – San Pedro shelf, Santa Barbara Channel; see Dailey et al. 1993) and the southern portions of the Santa Maria Basin (southern central California offshore, offshore Point Conception – Point Arguello). The marine mammals of California are described by Orr and Helm (1989) and Perrin et al. (2002). General species characterization data for seals and sea lions were derived from Reidman (1990). Survey data on marine mammals off the U.S. west coast, including offshore California, are provided in Barlow (1994, 1997).

Cetaceans

Thirty-three species of cetaceans may occur in the Southern California Bight (Koski et al. 1998; **Table 5.7**). These include 25 species of toothed whales and eight species of baleen whales. Many species are migratory or occur only seasonally in the area, while others are year-round residents. Common species include Dall's porpoise (*Phocoenoides dalli)*, Pacific white-sided dolphin (*Lagenorhynchus obliquidens*), Risso's dolphin (*Grampus griseus*), short-beaked common dolphin (*Delphinus capensis*), northern right whale dolphin (*Lissodelphis borealis*), and gray whale. Other species occur in relatively moderate or small numbers or are only occasionally sighted.

In the waters of the Southern California Bight, the sperm, northern right, humpback, blue, fin, and Sei whales are federally listed as endangered and protected

Table 5.7

Common and Scientific Names, Abundance, Status, and Seasonal Occurrence of Cetaceans That May Occur in the Southern California Bight (Adapted from: Department of the Navy 2002)

Species	Abundance	Status	Season
Odontocetes:			
Porpoises (Family Phocoenidae)			
Harbor porpoise	Rare	Protected	Winter
Phocoena phocoena			
Dall's porpoise	Common	Protected	Year-round resident
Phocoenoides dalli			
Dolphins (Family Delphinidae)			
Pacific white-sided dolphin	Common	Protected	Year-round resident
Lagenorhynchus obliquidens			
Risso's dolphin	Common	Protected	Year-round resident
Grampus griseus			
Bottlenose dolphin	Rare	Protected	Year-round resident
Tursiops truncatus			
Short-beaked common dolphin	Common/Abundant	Protected	Year-round resident
Delphinus capensis			
Long-beaked common dolphin	Uncommon	Protected	Year-round resident
Delphinus capensis			
Northern right whale dolphin	Common	Protected	Winter/spring
Lissodelphis borealis			
Short-finned pilot whale	Uncommon	Strategic	Year-round resident
Globicephala macrorhynchus			
Striped dolphin	Occasional	Protected	Summer/fall
Stenella longirostris			
Spinner dolphin	Rare	Protected	Summer
Stenella longirostris			
Spotted dolphin	Rare	Protected	Summer
Stenella attenuata			

Table 5.7. Common and Scientific Names, Abundance, Status, and Seasonal Occurrence of Cetaceans That May Occur in the Southern California Bight (Adapted from: Department of the Navy 2002) (continued).

Species	Abundance	Status	Season
Rough-toothed dolphin	Rare	Protected	Summer
Steno bredanensis			
Killer whale	Uncommon	Protected	Year-round resident
Orcinus orca			
False killer whale	Rare	Protected	Summer
Pseudorca crassidens			
Beaked whales (Family Ziphiidae)			
Cuvier's beaked whale	Uncommon	Protected	Unknown
Ziphius cavirostris			
Baird's beaked whale	Rare	Protected	Late spring-early fall
Berardius bairdii			
Blainville's beaked whale	Rare	Protected	Unknown
Mesoplodon densirostris			
Hector's beaked whale	Rare	Protected	Unknown
M. hectori			
Stejneger's beaked whale	Rare	Protected	Unknown
M. stejnegeri			
Hubb's beaked whale	Rare	Protected	Unknown
M. carlhubbsi			
Gingko-toothed whale	Rare	Protected	Unknown
M. ginkgodens			
Sperm whale (Family Physeteridae)			
Sperm whale	Uncommon	Endangered, Depleted, Strategic	Fall/winter
Physeter macrocephalus			
Pygmy sperm whales (Family Kogiidae)			
Pygmy sperm whale	Rare	Protected	Year-round resident
Kogia breviceps			
Dwarf sperm whale	Possible visitor	Protected	Summer
Kogia simus			

Table 5.7. Common and Scientific Names, Abundance, Status, and Seasonal Occurrence of Cetaceans That May Occur in the Southern California Bight (Adapted from: Department of the Navy 2002) (continued).

Species	Abundance	Status	Season
Mysticetes:			
Right whales (Family Balaenidae)			
Northern right whale	Rare	Endangered	Spring
Eubalaena (=Balaena) glacialis			
Gray whale (Family Eschrichtiidae)			
Gray whale	Common	Protected	Migrant, winter/spring
Eschrichtius robustus			
Rorquals (Family Balaenopteridae)			
Humpback whale	Uncommon	Endangered, Depleted, Strategic	Migrant, spring/fall
Megaptera novaeangliae			
Blue whale	Uncommon	Endangered, Depleted, Strategic	Summer/fall
Balaenoptera musculus			
Fin whale	Uncommon	Endangered, Depleted, Strategic	Year-round resident
B. physalus			
Sei whale	Rare	Endangered, Depleted, Strategic	Spring/summer
B. borealis			
Bryde's whale	Rare	Protected	Summer
B. edeni			
Minke whale	Uncommon	Protected	Spring/summer
B. acutorostrata			

under the ESA. Population trends evident among the endangered cetaceans occurring in the waters off California differ among species. From 1980 onwards, sperm whale numbers have been variable but no trend has been evident (Carretta et al. 2002). Sperm whales are usually found in deeper waters seaward of the continental slope during fall and winter.

Humpback whale numbers have apparently increased in the waters off California since 1980 at approximately 8% per year (Carretta et al. 2002). The humpback population estimates for the entire North Pacific have also increased from an estimated 1,200 animals in 1966 to approximately 6,000 to 8,000 in 1992. Humpback whales are found in southern California waters primarily during spring and fall migrations, but feeding concentrations also occur during the summer.

There are some indications that blue whale populations in coastal waters of California may be increasing. It is unclear whether increased numbers of blue whales are due to an increase in the population or to more extensive use of California waters for feeding. Larkman and Viet (1998) did not detect any increase in blue whales in the Southern California Bight from 1987 to 1995. Blue whales occur in southern California waters primarily during late spring and summer, where they feed in deep offshore waters.

There is some indication that fin whales may be increasing off California, although the trends are not significant (Carretta et al. 2002). Fin whales occur in southern California waters during the summer along the continental slope and offshore waters. The highest concentrations are reported from offshore waters north of Point Conception.

There are no data available on current population trends for Sei whales. In southern California, Sei whales occur in small numbers primarily during the spring and summer in offshore waters but may also occur in waters over the continental slope.

The northern right whale is probably the most endangered of the large whale species (Koski et al. 1998). Despite full protection since 1931, the North Pacific population is estimated at between 50 and 200 animals (American Cetacean Society [ACS] 2003a). Recent sightings have been near shore in continental shelf waters, but there have been more opportunities for sightings in inshore than offshore waters (Koski et al. 2002). Most sightings have been of single animals in winter or early spring.

Some cetaceans have displayed remarkable population recoveries in recent years. The gray whale was recently removed from the U.S. list of endangered species, and the eastern North Pacific population now numbers between 19,000 and 23,000 animals (ACS 2003b). Gray whales occur in both inshore and offshore waters of California during their southward migration from late December through February and their northward migration from mid-February through May.

Pinnipeds

Six species of pinnipeds may occur in the waters of the Southern California Bight (**Table 5.8**), including harbor seal, northern elephant seal, California sea lion, Steller sea lion, and Guadalupe and northern fur seals.

Table 5.8

Common and Scientific Names, Abundance, Status, and Seasonal Occurrence of Pinniped Species and the Southern Sea Otter (Mustelid) Present in the Southern California Bight

Species	Occurrence	Status	Season
Seals (Family Phocidae)			
Harbor seal	Common	Protected	Year-round
Phoca vitulina			
Northern elephant seal	Common	Protected	Year-round
Mirounga angstirostris			
Fur seals and sea lions (Family Otariidae)			
California sea lion	Common	Protected	Year-round
Zalophus californianus			
Steller sea lion	Rare	Threatened, depleted, strategic	Vagrant
Eumetopias jubatus			
Guadalupe fur seal	Rare	Threatened, depleted, strategic	Unknown
Arctocephalus townsendi			
Northern fur seal	Common	Protected	Year-round
Callorhinus ursinus			
Sea otter (Family Mustelidae)			
Southern sea otter	Rare	Threatened, depleted, strategic	Year-round
Enhydra lutris nereis			

The California harbor seal population has dramatically increased since the 1960's and may be around 30,000 animals (Koski et al. 1998). In some areas, the populations may be stable or declining either because they have reached their carrying capacities or because they may be limited by competition with northern elephant seals. During most of the year, harbor seals are found in nearshore areas where they feed in waters from 10 to 120 m in depth.

The northern elephant seal population in California has increased since 1900. The California population is estimated at approximately 84,000 animals, most of which use haul-outs on islands off southern California with the largest numbers on San Miguel and San Nicolas islands (Koski et al. 1998). Northern elephant seals also breed on islands of the west coast of Mexico, and some of the population increases in the southern California stock may have resulted from emigration of Mexican seals. Northern elephant seals spend most of the year feeding in offshore waters but haul out on beaches to give birth, breed, and molt. Elephant seals feed in deeper water than harbor seals and may dive to 800 m.

The California sea lion is the most common pinniped in Southern California. The California sea lion population may number around 200,000 animals, and more than 95% of the U.S. stock is associated with haul-outs on San Miguel and San Nicolas islands (Koski et al. 1998). Breeding haul-outs are also located on islands off the west coast of Mexico and the Sea of Cortez. Smaller haul-outs occur from Point Conception to the California/Oregon border. After breeding, California sea lions migrate to offshore feeding areas and may move as far north as Puget Sound and British Columbia.

The western stock of the Steller sea lion is listed as endangered, and the eastern stock is listed as threatened under the ESA and is being considered for endangered status due to declines in the Alaskan populations. Steller sea lions formerly bred on San Miguel Island but the southernmost breeding colony is now Año Nuevo Island off central California. They are rarely sighted in the waters off southern California. Steller sea lion is considered as depleted under the MMPA, and the Eastern stock, which occurs in California waters, is considered a strategic stock.

The Guadalupe fur seal was near extinction in the late 1800's due to commercial sealing activities. The main breeding colony is located on Isla Guadalupe off the coast of Baja California. In 1997, a second colony was discovered south of Isla Guadalupe on Isla Benito del Este and a pup was reported on San Miguel Island. Over the last 30 years, the Guadalupe fur seal annual growth rate has been 13.7% (Koski et al. 1998; Carretta et al. 2002) and the population numbers around 7,000 animals, most of which are centered on Isla Guadalupe. The Guadalupe fur seal appears to be expanding its range, and the number of sightings in the waters off southern California has been increasing in recent years. The Guadalupe fur seal is listed as threatened under the ESA and as a depleted and strategic stock under the MMPA.

Most of the U.S. population of northern fur seals breeds on the Pribilof Islands in the Bering Sea. Small colonies also are located on Bogoslof Island in the southern Bering Sea and on San Miguel Island off southern California. The San Miguel Island stock originated from the Pribilof Island stock during the late 1950's or early 1960's and was discovered in 1968 (Carretta et al. 2002). Since then, the colony has increased steadily with the exception of declines in 1983 and 1998 that were associated with El Niño Southern Oscillation events. Although the eastern Pacific stock from the Bering Sea was listed as depleted under the MMPA in 1988, the San Miguel Island stock is not considered to be depleted, or threatened or endangered under the ESA. The most recent estimate for the San Miguel Island stock is 4,336 animals. During the winter, female and juvenile northern fur seals from the depleted eastern Pacific stock of the Bering Sea migrate south, and fur seals in the waters off southern California may be either from this stock or the San Miguel Island stock (Koski et al. 1998).

Mustelids

The southern sea otter is the only other marine mammal known to occur in the waters of the Southern California Bight. Sea otters were exploited for their pelts during the 1700's and 1800's; their numbers dropped drastically, and they were extirpated from some areas. In 1911, sea otters were given full protection under the Fur Seal Treaty. Recovery efforts have been variably successful. The State of Alaska successfully reintroduced sea otters into areas of unoccupied habitat, and sea otter numbers have been increasing (Alaska Department of Fish and Game [ADFG] 2002a). The southern or California population has grown more slowly and is restricted primarily to coastal waters from Point Año Nuevo to Purisima Point but has been expanding its range south into the western portions of the Santa Barbara Channel area. A small transplanted population is also located around San Nicolas Island, results of an effort to establish a colony removed from the mainland population. The California southern sea otter population contains approximately 2,400 animals (Koski et al. 1998) and is listed as threatened under the ESA; it is categorized as depleted and listed as a strategic stock under the MMPA.

5.3.3 Alaska OCS Region

Federal OCS oil and gas production activities offshore Alaska are restricted to two separate regions – Cook Inlet and nearshore waters of the Beaufort Sea. Platform removal is only expected to occur in the Cook Inlet (i.e., only gravel islands are used for offshore oil and gas production on the Beaufort Sea shelf); at present, only one platform occurs in Federal OCS waters of Cook Inlet. The following discussion of marine mammals in the Alaska OCS Region will be focused on the Cook Inlet region. Marine mammals of Alaska are described in Angliss and Lodge (2002), Perrin et al. (2002), and Wynne (1997).

The most intensely studied marine mammal in the Cook Inlet area is the beluga whale (*Delphinapterus leucas*). The Cook Inlet beluga population occurs in the inlet and Shelikof Strait region, although wanderers have been seen east to Yakutat Bay and to Kodiak Island. Belugas are toothed whales that often ascend large rivers, where they feed on anadromous fishes and appear to be unaffected by salinity changes. During the summer they also feed on herring, capelin, smelt, arctic and saffron cods, flatfishes, sculpins, octopus, squid, shrimp, crabs, and clams (ADFG 2002b).

The Cook Inlet beluga stock was subjected to unregulated harvest until 1999 and was listed as depleted under MMPA in May 2000 (*Federal Register* 65:34,590). The Cook Inlet stock is now managed with a small, regulated harvest. NMFS has conducted annual aerial surveys during June and July for beluga whales and other marine mammals in Cook Inlet since 1993. Index counts, which are uncorrected for whales that may have been outside of the observers' view, have ranged from 174 to 217 since 1998 (Rugh et al. 2003). These counts are lower than those reported from 1993 to 1997 that ranged from 264 to 324. In 2003, as in most years, belugas were found in small groups near river mouths along the northwestern shores of upper Cook Inlet, in particular near Beluga River, Susitna River, Little Susitna River, and across the middle of Knik Arm, as well as along the shores of Chickaloon Bay; no belugas were reported south of the Forelands in lower Cook Inlet. Prior to 1996, it was not uncommon to see groups of belugas south of the Forelands, but since then there have been few sightings in the lower inlet (Rugh et al. 2003).

During the NMFS 2003 aerial survey, harbor seal (*Phoca vitulina*) was the only other marine mammal observed in upper Cook Inlet (Rugh et al. 2003). Harbor seals are generally associated with coastal areas, although they occasionally are observed well offshore. In Alaska, harbor seals feed on pollock, Pacific cod, capelin, eulachon, Pacific herring, salmon, octopus, and squid (ADFG 2002c). During the NMFS 2003 survey, harbor seals were concentrated (i.e., up to 50 individuals) in upper Cook Inlet at Chickaloon Bay, and between the Beluga and Susitna rivers, where as many as 200 individuals were sighted. In the lower inlet, harbor seals were concentrated in Kachemak Bay (140 individuals at Bradley River), Big River (130 individuals), and in or near Tuxedni Bay (100 individuals). There was a total of 36 harbor seal sightings totaling 974 individuals. No marine mammals were reported in Cook Inlet north of Kachemak Bay during the NMFS 2003 aerial survey other than beluga whales and harbor seals.

Steller sea lions (*Eumetopias jubatus*) were reported during the 2003 aerial surveys in lower Cook Inlet near Elizabeth Island, where 76 animals were hauled-out on the south shore and one other seal lion was seen in the water nearby. The Alaska population of Steller sea lions was estimated at approximately 242,000 animals in the 1970s, but declined by about 50% by the mid-1980's. The reasons for the decline are unclear but may be related to food availability and/or global climate change. Under the ESA, Steller sea lions west of Cape Suckling, Alaska are listed as endangered and those east of Cape Suckling are listed as threatened. Steller sea lions feed on a variety of fishes, including pollock, flounder, herring, capelin, Pacific cod, salmon, rockfish, sculpins, and invertebrates such as squid and octopus (ADFG 2002d) and may compete with commercial fisheries.

Three other pinniped species – northern fur seal (*Callorhinus ursinus*), northern elephant seal (*Mirounga angustirostris*), and Pacific walrus (*Odobenus rosmarus*) – may also occur in Cook Inlet (MMS 1996). These species occasionally occur in the lower Cook Inlet/Shelikof Strait area but were not observed during the 2003 aerial survey.

During the 2003 Cook Inlet aerial surveys, sea otters (*Enhydra lutris*) were common in lower Cook Inlet, as in previous years (Rugh et al. 2003). Sea otters were exploited for their pelts during the 1700's and 1800's; their numbers dropped drastically, and they were extirpated from some areas. As noted previously, sea otters were given full protection under the Fur Seal Treaty in 1911. The State of Alaska successfully reintroduced sea otters into areas of unoccupied habitat, and by the mid-1970's the Alaskan population numbered between 110,000 and 160,000 animals (ADFG 2002a). During the 2003 aerial surveys in Cook Inlet, there were 39 sightings totaling 291 otters in groups of from 1 to 50 individuals. All sightings were in areas south of Kachemak Bay, and no sea otters were reported from the upper inlet.

Humpback whales (*Megaptera novaeangliae*) and fin whales (*Balaenoptera physalus*) were reported at three locations along the southern limits of Cook Inlet during the 2003 aerial survey: 1) between Augustine Island and the Barren Islands (i.e., five humpback, three fin whales); 2) north of the Barren Islands (12 humpback, 13 fin whales); and 3) west of Kachemak Bay (three humpback whales sighted on two survey dates). Other cetaceans that can occur in the area but were not observed during the 2003 survey include killer whale (*Orcinus orca*), harbor porpoise (*Phocoena phocoena*), Dall's porpoise (*Phocoenoides dalli*), Pacific white-sided dolphin (*Lagenorhynchus obliquidens),* gray whale (*Eschrichtius robustus*), minke whale (*Balaenoptera acutorostrata*), Baird's beaked whale (*Berardius bairdii*), and Cuvier's beaked whale (*Ziphius cavirostris*) (MMS 1996). In addition, sperm whale (*Physeter macrocephalus),* Sei whale (*Balaenoptera borealis*), right whale (*Eubalaena [=Balaena] japonica*), and blue whale (*Balaenoptera musculus*) may wander into the area.

5.3.4 Marine Mammal Survey Data Limitations

Effective monitoring and mitigation of the impacts of explosives on marine mammals depends on the ability to detect them. Visual detection is a function of the group size, time spent at the surface, and behavior of the animals. Large groups of small odontocetes that travel in groups of a hundred, make short shallow dives, and make a habit of leaping into the air are more likely to be seen than manatees that are found in small groups and do not leave much of an indication of their presence at the surface. Species that make long dives, such as sperm whales and beaked whales, may not spend much time at the surface and so will be difficult to detect visually.

One of the mitigation measures for underwater detonations is aerial surveys to detect the presence of marine mammals and to suspend the explosion if mammals are present. The g(0) function in (e.g., see **Table 5.6**) is the probability of an animal being at the surface at any instance in time. This function and specific density of a particular species at the time and place of the test (Davis et al. 2000) can be used to design a survey program that is optimal for detecting marine mammals.

CHAPTER 6
ENVIRONMENTAL CONSEQUENCES

6.1 Marine Fishes

Those who collect fish for a living (fishers and ichthyologists) have long exploited the fact that fishes readily succumb to underwater explosions. Islanders from the Indo-Pacific region (Indonesia, Papua New Guinea, and the Philippines) have fished with explosives since World War II when ordnance and explosives left behind provided the basis for a new and effective method of harvesting reef fish (Ronquillo 1950; Alcala and Gomez 1987; Saila et al. 1993; McManus et al. 1997; Pet-Soede et al. 1999). In these areas, effects of blast fishing on coral reef habitats and fish populations have been the primary concern among resource managers and conservationists.

Similarly, blast fishing also has a history in the U.S. For example, Carr (1996) tells of individuals using partial sticks of dynamite (called "cut bait") to kill or stun fishes from freshwater streams and springs in Florida. Engaging in a more professional form of blast fishing, fish researchers seeking assessments of local fish assemblages often used explosives in marine (e.g., Russell et al. 1978; Williams and Hatcher 1983) and freshwater (Metzger and Shafland 1986; Bayley and Austen 1988) settings. If carefully deployed, explosives provided quantitative samples of discrete areas without greatly damaging the habitat structure. This was because the killing shock waves emanating from the blast attenuate rapidly, resulting in a restricted lethal zone. Explosive sampling offered researchers an alternative to liquid ichthyocides such as rotenone that can drift out of a prescribed study area to create extensive and unwanted fish kills. Nevertheless, because of safety and public perception issues, ichthyologists rarely use explosives to sample fishes.

Although these purposeful uses of explosives to collect fishes are now against the law or in general disfavor, there are many situations in underwater construction, geophysical surveying, and demolition where fish kills are an unwanted side-effect of explosive use. Explosive removal of offshore oil and gas structures is a primary example of a situation where unwanted fish kills have become part of the process. Oil and gas structures in the Gulf of Mexico and Pacific OCS Planning Areas attract and concentrate large numbers of fishes as de facto artificial reefs (Sonnier et al. 1976; Gallaway and Lewbel 1982; Putt 1982; Continental Shelf Associates, Inc. 1982; Stanley and Wilson 1990, 1998; Love et al. 2000). Consequently, when structures are removed using explosives, high numbers of resident fishes can be killed (Gitschlag et al. 2000).

Many of the species killed or injured within OCS Planning Areas are managed under the Magnuson-Stevens Fishery Conservation and Management Act (16 U.S.C. § 1801-1882). Platforms in the Gulf of Mexico provide habitat for members of the snapper-grouper (reef fish) management unit, red drum management unit, coastal migratory pelagic management unit, and the highly migratory species management units managed by the Gulf of Mexico Fishery Management Council. In the Pacific OCS

Planning Area, species from the groundfish management unit under the jurisdiction of the Pacific Marine Fisheries Commission inhabit offshore platforms. As the platform removal program progresses, resource managers from MMS and NOAA-F (NMFS) need to determine whether there are any adverse effects to local populations and the ecosystems they inhabit.

6.1.1 Lethal Effects of Underwater Explosions on Fishes

Effects of underwater explosives on fishes have been fairly well documented (see reviews by Christian 1973; Hill 1978; Baxter et al. 1982; Lewis 1996; and Keevin and Hempen 1997). The few generalities that have emerged from empirical studies indicate that at very close range, underwater explosions are lethal to most fish species regardless of size, shape, or internal anatomy; however, at greater distances from the source, species with gas-filled swimbladders suffer higher mortality than those without swimbladders.

Studies also suggest that larger fishes are generally less susceptible to death or injury than small fishes at the same distance from the source; elongated forms that are round in cross-section are less at risk than deep-bodied forms; and orientation of fish relative to the shock wave may affect the extent of injury. The results of most studies are dependent upon specific biological, environmental, explosive, and data recording factors. The following subsections contain reviews of available information with attention to lethal and sublethal effects of underwater explosions on fishes. Under the lethal heading, causes of death, documented fish kills (particularly those associated with platform severance), experimental studies, and predictive modeling of lethal ranges are described.

Causes of Injury

Understanding lethal effects of underwater explosion requires identification of causes of death and factors that contribute to variation in those causes. For most situations, cause of death in fishes has been massive organ and tissue damage and internal bleeding. These causes are related to fish size, species, and to a lesser extent orientation with respect to the incoming shock wave.

Fish are most often killed or injured by the shock wave generated by an underwater explosion. The precise component of the shock wave responsible for injury is not known. Damage is usually found in visceral organs, but also can include general tissue damage to fishes in close proximity to the detonation site. Field studies of injuries associated with free swimming and experimentally caged fishes have documented that most lethal injuries involve damage to visceral organs (e.g., Alpin 1947; Ronquillo 1950; Teleki and Chamberlain 1978; Wiley et al. 1981; Linton et al. 1985). The most commonly injured organs are those with air spaces that are affected by the explosion's shock wave passing through the body of the fish. These spaces include the body cavity, pericardial sac, and gut, but the primary air space in fishes is the swimbladder. Swimbladder injuries were most frequently observed in field monitoring and experimental investigations (e.g., Christian 1973; Wiley et al. 1981; Linton et al. 1985; Keevin and Hempen 1997).

The swimbladder is a gas-filled sac that functions as a hydrostatic organ allowing the fish to control its buoyancy. Gases from the blood are exchanged with the swim bladder through a circulatory apparatus called the rete mirable (wonderful net) (Jones and Marshall 1953). When pressures oscillate rapidly as they do when an explosive shock wave passes through the fish, the swimbladder will expand and contract rapidly to the point of rupturing (Wiley et al. 1981). There is evidence that damage to proximate organs, particularly the kidneys (which lie just dorsal to the swimbladder in most species), can occur when the expanding swimbladder compresses them (Keevin and Hempen 1997).

Swimbladders vary in structure and presence on broad phylogenetic scales (Liem 1988). Swimbladders are a characteristic of bony fishes not present in sharks, rays, and their allies. Within the bony fishes there are phylogenetic divisions that include, among other traits, modifications to the swim bladder (Jones and Marshall 1953; Liem 1988). In some ancestral fishes the swimbladder is connected via a pneumatic duct to the esophagus, allowing the fish to gulp air. This condition is called physostomus. Catfishes, carps, herrings, salmons, and tarpon are physostomus. Species exhibiting the derived condition (no connection to the esophagus) are called physoclistus. Although physoclistus species use the swimbladder primarily as a hydrostatic organ, some use it to aid in hearing and in sound production (Hawkins 1986). Most common bony fishes are physoclistus, however some, including flatfishes (Pleuronectiformes), eels (Anguilliformes), and others, do not have swimbladders.

Fish without swimbladders are certainly less vulnerable to shock wave impacts at a distance from underwater explosions, but they will be killed by physical force located very close to the explosive source. Goertner et al. (1994) recorded immediate death for hogchoker (*Trinectes maculatus*) and summer flounder (*Paralichthys dentatus*) specimens placed within 0.5 to 2 m from the explosive source. Individuals were killed by loss of blood as a result of hemorrhaging in the gills. This may have been caused by radial oscillation of gas microbubbles (0.1 mm diameter) in the gill epithelium. In addition, there was hemorrhaging in the cranium caused by differential motion of the otoliths.

Of the 55 fish taxa killed during platform removals in the Gulf of Mexico (Gitschlag et al. 2000), most were swimbladder species. Most were physoclists, but several physostomes were included. The only taxa reported that do not have swimbladders were an unidentified eel, searobin (*Prionotus* sp.), and molley miller (*Scartella cristata*). The top species killed were generally deep-bodied types that were surely ventrally exposed to removal blasts buried in the structures.

Other factors contributing to injury or death are fish size, body shape, orientation, and species. Yelverton et al. (1975) experimentally determined that LD_{50} (50% mortality) for various fish species exposed to explosions increased with weight of the fish. They used fishes weighing from 0.02 to 800 g to performed dose-response experiments at varying distances from the explosive source. Their dose-response figure, including LD_{50}, LD_1, and no effect curves, is reproduced in **Figure 6.1.**

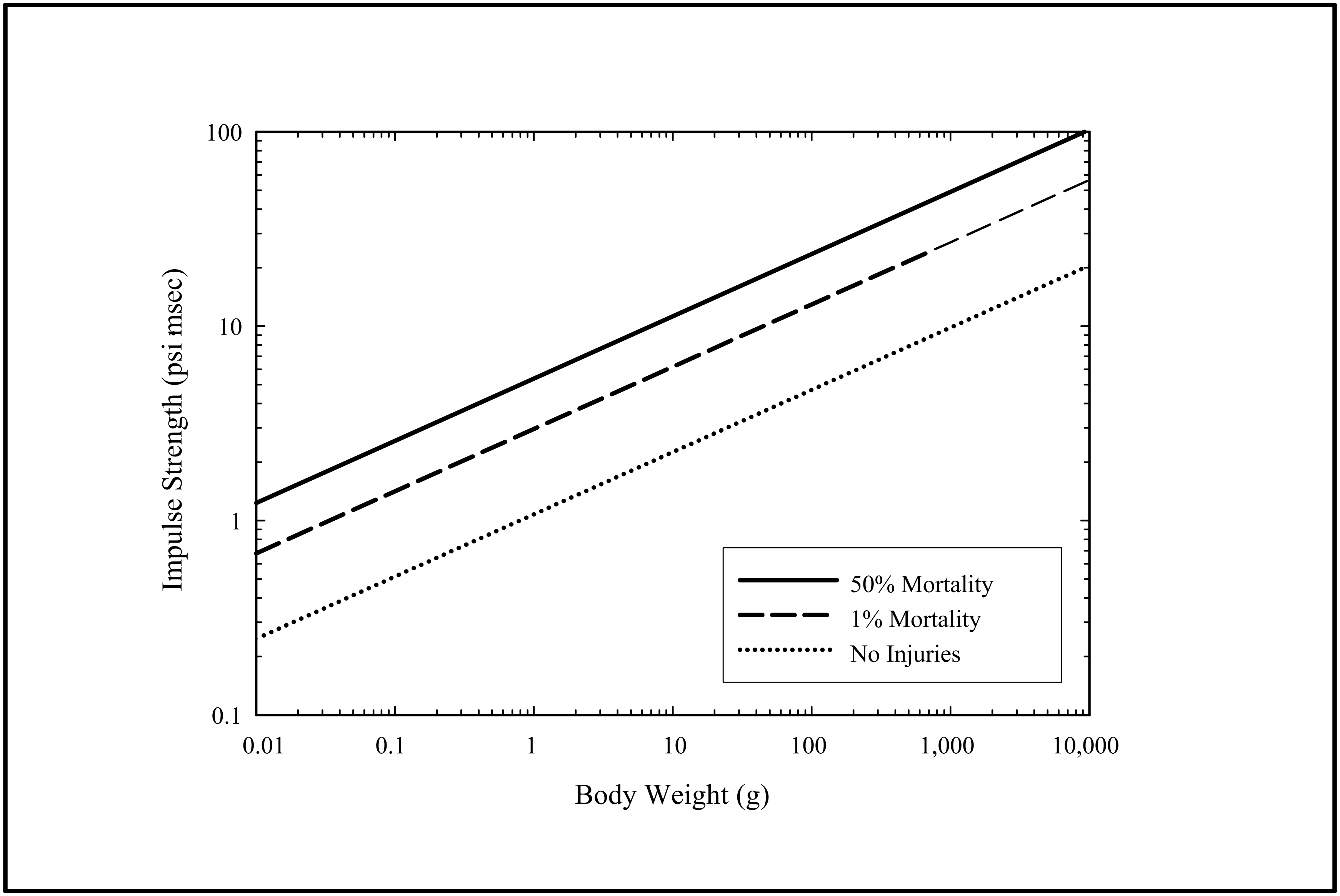

Figure 6.1. Response of fish to underwater blast as a function of impulse strength and body weight (Adapted from: Yelverton et al. 1975).

Orientation of the fish relative to the oncoming shock wave can greatly influence the degree of injury sustained by caged fishes (Sakaguchi et al. 1976). Fishes facing head on to the wave sustained less injury than fishes exposed broad-side to the shock wave. Fishes with the ventral side exposed were most damaged. This aspect has not been investigated for a wide range of species.

Contributing most to variation and uncertainties in the experimental setting are species-specific vulnerability to underwater shock waves. Some asserted that physostomus species would be less susceptible to pressure changes because of the outside connection to the swimbladder (Christian 1973; Teleki and Chamblerlain 1978). However, pressure changes created by underwater explosions are much too rapid for physostomus fish to respond physiologically. Even though there is an opening to the outside through the pneumatic duct, the opening is very small and structurally unable to expel gas at a rate that would prevent rapid expansion of the swimbladder. This fact has prompted some to suggest that there is no practical difference in the vulnerability of physostomes and physoclists. Within physoclists there are species-specific differences in swimbladder structure that may contribute to variation in observed injuries (Wiley et al. 1981). Species-specific body morphology and rigidity have been suggested to affect the injury level in some species. Expanding swimbladders will injure adjacent organs, particularly the kidneys. In species such as toadfish (*Opsanus tau*), where the swimbladder is positioned away from vital organs, there may be fewer mortalities (Wiley et al. 1981).

Documented Effects of Underwater Explosions on Fishes

Monitoring studies have documented that fishes are killed during planned underwater explosions. Investigators in these studies have collected representative samples of fishes killed during planned explosions and in some cases tried to estimate regional or local scale population effects of the kills associated with underwater explosions (Alpin 1947; Ronquillo 1950; Fry and Cox 1953; Nix and Chapman 1985; Gitschlag and Herczeg 1994; Gitschlag et al. 1997, 2000). Fishes collected during these studies have mostly been recovered floating at the waters surface following an explosion. Studies that employed scuba divers to retrieve fishes from the bottom following an explosion indicate that as few as 3% of the specimens killed during a blast may float to the surface (Gitschlag et al. 2000). Other impediments to accurate characterization of fish kills include currents and winds that may transport floating fishes out of the sampling area before field crews can recover them. Additionally, predation by seabirds or other fishes can be substantial, particularly on smaller specimens.

Of the monitoring studies available, the most relevant to this review were the monitoring of fishes killed (and floating) around oil and gas structures in the northern Gulf of Mexico from 1986 to 1998 by the NMFS (Gitschlag and Herczeg 1994; Gitschlag et al. 1997, 2000). Monitored structures included platforms, submerged wells, caissons, and flare piles. In 1992, 42% of the removals occurred in water depths of ≤15 m, and 55% occurred in depths ranging from 15 to 60 m. Most removals occurred offshore Louisiana in an area bounded by Grand Isle, LA to the east and the Sabine River to the west. Observers only counted fish floating on the surface during these surveys. Most were killed during platform removals, followed by caisson removals, submerged structures, and flare piles (**Table 6.1**). The average number of floating fish per structure was 567 for platforms, 133 for submerged wells, 109 for caissons, and 41 for flare piles (**Table 6.1**). Numerically dominant fishes killed, in decreasing order of abundance, were spadefish (*Chaetodipterus faber*), red snapper (*Lutjanus campechanus*), vermilion snapper (*Rhomboplites aurorubens*), hardhead catfish (*Arius felis*), blue runner (*Caranx crysos*), sheepshead (*Archosargus probatocephalus*), tomtate (*Haemulon aurolineatum*), and lane snapper (*Lutjanus synagris*).

Table 6.1

Estimated Number of Dead Fishes Floating at the Surface After Detonations During 1986 to 1998 (From: Gitschlag et al. 2000)

Structure Type	Number of Structures	Average Number of Floating Fish per Structure	Total Estimated Number of Floating Fish
Platform	742	567	420,932
Submerged well	57	133	7,554
Caisson	252	109	27,372
Flare pile	7	41	285

As previously mentioned, the platform monitoring studies described above only collected floating fishes. In an effort to gather more quantitative and realistic measures of fishes killed during explosive removals, Gitschlag et al. (2000) collected both floating and sinking fishes killed during removal of nine platforms in the northern Gulf of Mexico. Scuba divers collected dead fishes that had settled to the seafloor around these platforms. Study platforms were located in 14 to 36 m water depths and bounded by Longitudes 89˚ and 95˚ W (eight offshore of Louisiana and one offshore of Texas). Investigators sampled both floating and sinking fishes at various distances up to 100 m from the study platforms. They also employed pre-blast tagging of fishes to provide an estimate of pre-blast population sizes using standard mark-recapture methods. Only fishes greater than 8 cm were tallied for the mortality estimates in the report (Gitschlag et al. 2000).

A total of 30,315 individuals represented by 55 fish taxa in 23 families (combined floaters and sinkers >8 cm total length) was recorded from the nine platforms. The number of taxa per platform averaged 14.4 and ranged from 8 to 20. The number of individuals estimated at each platform averaged 3,390 and ranged from 1,765 to 5,216. These values indicate the underestimation of mortality that results from counting only floating fishes. Spadefish, red snapper, sheepshead, blue runner, and gray snapper collectively contributed 90% of the total numbers sampled. Explanatory factors such as platform age, water depth, longitude, surface salinity, surface temperature, and season were weakly correlated with mortality of any of these species.

Most of the fishes recovered by Gitschlag et al. (2000) were found within 25 m of the platform. Numbers decreased with distance out to 100 m, the greatest extent to where divers searched for dead fishes. This suggests that most of the fishes were very close to the structure, corroborating Stanley and Wilson's (1998, 2000) estimate of 18 to 50 m as the primary distance envelope for platform-associated fishes.

Although the study by Gitschlag et al. (2000) was very thorough in the documenting of fishes killed by platform removals, the authors point out that any generalization beyond the geographical area, water depth range, season, fish species, and size ranges should be done with caution.

Monitoring studies document species composition and relative numbers killed, but they rarely record information on the shock waves or provide insights into lethal ranges for various explosives. Researchers have been searching for the precise component of the shock wave that will provide a general prediction of lethal zones for underwater explosions (e.g., Hubbs and Rechnitzer 1952; Linton et al. 1985; Goertner et al. 1994; Keevin and Hempen 1997). Physical properties of shock waves that have been empirically or theoretically correlated with fish mortality are impulse level, which is the time-pressure integral of the shock wave reported in Pa-s units; energy flux density, which is the rate of energy transport over a unit area reported as J/m^2; and peak pressure, the maximum pressure of the initial shock wave reported in Pa.

Peak pressure is often considered an important component of the shock wave in experimental situations. A 60% reduction in relative pressure was considered to be sufficient to burst the swimbladder of a physoclistus fish (Jones 1951, 1952). Hubbs and Rechnitzer (1952) reported lethal threshold peak pressures ranged from 40 to 70 psi (276 to 482 kPa) for dynamite. These investigators also found that black powder charges as high as 1,100 kPa were not lethal to fishes. These observations were confirmed in California coastal waters by Fry and Cox (1953) and by Ferguson (1962) for freshwaters. Black powder has a slow detonation (deflagration) velocity (i.e., relatively slow rise time and peak pressure; see **Chapter 3**, **Table 3.1** and **Chapter 4**). Keevin and Hempen (1997) found that detonation velocity was not a factor in fish mortality with commercially available explosives. They believe that the slow rise time (to peak) pressure was the characteristic that made black powder charges less lethal to fishes.

Keevin and Hempen (1997) measured energy flux density, impulse strength, and peak pressure associated with experimental detonations to determine lethal ranges for caged bluegill (*Lepomis macrochirus*). All three measures were correlated with fish mortality, but impulse strength varied the least. They found an immediate increase in damage to internal organs at levels above 700 kPa peak pressure, 50 pa-s impulse (from the first positive wave), and 40 J/m^2. Mortality increased at levels above 500 kPa, 40 pa-s, and 20 J/m^2. The lower levels for mortality were due to the mortality scoring system used that treated minor injuries as deaths. Measured LD_{50} values for bluegill in these trials were about 40 m.

Effects on Early Life Stages

There have been few investigations of the effects of underwater explosions on early life stage (egg, larval, juvenile) fishes. Fitch and Young (1948) reported that larval anchovies died when exposed to underwater blasts off California, and Nix and Chapman (1985) found that anchovy and smelt larvae died following the detonation of buried charges. Yelverton et al. (1975) demonstrated that smaller sized fishes were less sensitive to shock waves than larger ones at similar distances from the explosive source. The LD_{50} for larval guppy (*Lebistes reticulatus*) was estimated to be 1.7 psi ms (11.7 kPa-s) (Brown 1939). Settle et al. (2002) reported total injury dose (the sum of lethal and sublethal fractions) of 8.9 Pa-s for spot and 5.3 Pa-s for pinfish.

As with adult fishes, the presence of a swim bladder contributes to internal damage in larval and juvenile fishes (Settle et al. 2002). Timing of swimbladder development varies with species, but its presence is important in the survival of larval fishes (Egloff 1996). Settle et al. (2002) used controlled cage experiments with two larval fish species, spot (*Leiostomus xanthurus*) and pinfish (*Lagodon rhomboides*) to determine lethal distances and to assess internal damage. Trauma to internal organs of test fishes was verified histologically by Govoni et al. (2002). Specimens exposed to the strongest shock waves had injured kidneys, swimbladder, liver, and pancreas. They stated that the most common injury to spot and pinfish was hematuria (damage to kidney tubules). Other trauma observed were hemorrhage within the coelom, swimbladder hemorrhage, liver hemorrhage, coagulative liver necrosis, and ruptured pancreas. These authors did not observe swim bladder rupture in field tests with larval spot and pinfish.

6.1.2 Sublethal Effects

Lethal consequences of underwater blasts involve traumatic damage to tissues and viscera in individuals within close range of the explosion. Some sublethal effects also may be expected due to this type of damage, but sublethal effects are more likely to involve impacts to hearing, sound detection, and sound production in individuals occurring at greater distances from explosion sources. These functions are important to the ecology and behavior of individuals, and may be temporarily or permanently altered by exposure to explosion (e.g., Myrberg 1981; Hawkins 1986). Any effects that would lead to reduced survival, growth, or reproductive output could lead to population level impacts. There is little information on sublethal effects of underwater explosions, however the effects would likely be in terms of unusual behavior. Such behavior would probably result from injury to hearing, orientation, and endocrine and nervous systems.

Teleost fishes detect pressure or shock waves in the inner ear and balance detection apparatus. The inner ear system detects a pressure wave when it is sufficiently strong to move the body of the fish relative to its otoliths, the stony structures that lie inside the semicircular canal system of the inner ear. There are three pairs of otoliths, and each is encased in an individual chamber lined with sensory hair cells upon which the otoliths are balanced. Otoliths are denser than the body of the fish (specific gravity of 2 or 3), and thus have more inertia than the fish. The hair cells have nervous connections that transmit the information on otolith position to the brain. Fishes also detect sound using the swimbladder and acoustico-lateralis system. Continental Shelf Associates, Inc. (2002) reviewed the general effects of noise on fishes. This report stated that all fish species investigated can hear, with varying degrees of sensitivity, within the frequency range of sound produced by underwater explosions. These sounds can mask the sounds normally used by fishes in their normal acoustic behaviors at levels as low as 60 to 80 dB (just above detection thresholds for many species). Levels as high as 160 dB may cause receiving fishes to change their behaviors and movements, which may temporarily affect the usual distribution of animals and commercial fishing. Continuous, long-term exposure to levels above 180 dB has been shown to cause damage to the hair cells of the ears of some fishes under some circumstances. These effects may not be permanent since damaged hair cells are repaired and/or regenerated in some fishes. However, McCauley et al. (2003) found irrepairable hair damage for species exposed to 180 dB seismic air gun noise. It is not clear if permanent hair cell damage could occur in response to underwater shock waves, but observations of behavioral alterations have been made during experimental studies. For example, Goertner et al. (1994) reported impaired swimming and disorientation in test fishes located well outside the lethal zone of the explosive source.

Shock waves produced by underwater explosions could affect behavior of larval fishes seeking shelter or settlement sites. Some reef fish larvae have been shown to respond to sound stimuli as a sensory cue to settlement sites (Stobutzki and Bellwood 1998; Tolimieri et al. 2000). Damage to hearing mechanisms in larvae could impair the ability of newly settled fishes to locate preferred substrate.

Sverdrup et al. (1994) examined the effects of seismic noise on endocrine function in farm-reared salmon. They found evidence of temporary vascular impairment of vascular endothelium, but no appreciable alteration of plasma levels of adrenaline or other stress hormones.

6.1.3 Prediction of Lethal Range

Field studies provided the impetus and data needed to develop and validate predictive models of lethal range or lethal zones for fishes using various physical properties of the shock wave produced by underwater explosions. These properties include compressional wave, peak pressure, impulse strength, bulk cavitation, and energy flux density. Several authors have reviewed the chronology and development of lethal range models for fishes (Christian 1973; Baxter et al. 1982; Lewis 1996; Keevin and Hempen 1997). The ability of models to accurately predict mortality or injury in fishes exposed to underwater shock waves is affected by numerous biological, environmental, explosive, and data acquisition factors (Keevin and Hempen 1997) (**Table 6.2**). Despite acknowledged uncertainties, models can be useful in predicting mortality and determining lethal zones expected for underwater explosions. Canada uses predictive models as part of their pre-explosive management program (Wright and Hopky 1998).

Table 6.2

Factors That Can Affect Fish Mortality, Making Precise Predictions of Mortality Difficult (From: Keevin and Hempen 1997)

Biological

- Size
- Shape
- Orientation
- Anatomy

Environmental

- Air-water roughness
- Water-bottom roughness
- Water bottom acoustic impedance (bottom type)
- Water temperature

Explosive

- Depth of explosive
- Relative bulk strength of explosive
- Surface, mid-column, or buried charge
- Pressure reduction from confined shot

Data Acquisition

- Accuracy of pressure transducers and recording equipment
- Pressure wave processing techniques
- Standardization of pressure wave form calculations

The most common models in use today are the impulse strength model (Hill 1978; Munday et al. 1986), energy flux density model (Sakaguchi et al. 1976; Baxter 1985), and the dynamical or swimbladder oscillation model (Wiley et al. 1981). Christian (1973) reviewed models based on charge weight and peak pressure and concluded that neither approach was appropriate, instead proposing that bulk cavitation should be considered as an important factor in fish kills because this process would cause rapid expansion and compression of swimbladders. Nevertheless, results from bulk cavitation models did not correlate well with observed fish mortality (Gaspin 1975), and increasing the charge weight did not result in a corresponding increase in the size of the cavitation zone as expected. Gaspin's (1975) attempts did reveal that total pressure drop was an important factor in mortality.

Impulse strength is considered the most important shock wave property for predicting damage or death in water depths less than 3 m (Baxter et al. 1982), and energy flux density was considered to be the best predictor in deeper water (Sakaguchi et al. 1976).

Young (1991) provides equations for calculating lethal ranges using the dynamic model. This dynamic model relates weight of charge to swimbladder oscillation parameters that are determined individually for each fish species. The dynamic model treats the swimbladder as a spherical gas bubble, and its motion under the influence of an explosive pressure wave is calculated. Fish damage is calculated under the parameters of the calculated motion; however, this approach depends upon fish size and water depth.

Young's (1991) equations were used to estimate a 10% mortality range or safe range, i.e., the area beyond which 90% of the fishes will survive a charge of given weight for reef and coastal pelagic fishes common to Gulf of Mexico oil and gas structures. The safe ranges for swim bladder fishes were calculated as follows:

$$R_{SF(meters)} = 43\ W_F^{-0.13} W_E^{0.28} D^{0.22}$$

where R_{SF} is safe range in meters, W_F is fish weight in pounds, W_E is charge weight in pounds, and D is charge depth in feet.

For non-swimbladder fishes, Young (1991) provided the following equation:

$$R_{SF} = 3.38\ W_E^{0.33}$$

Safe ranges for swimbladder fishes are clearly much greater than those estimated for non-swimbladder fishes (**Table 6.3**). The values for the reef fishes all exceed 200 m, and therefore exceed the 50 m envelope identified by Stanley and Wilson (1998, 2000) where most of the platform-associated species reside. Safe ranges for the coastal pelagic species are very close to the detonation source, possibly closer than these species would get.

It is important to note that all of the models discussed above, including those used in **Table 6.3**, assume mid-water or open water explosions. Severance of platform legs and associated structures obviously will employ buried charges. Clearly, there are differences in the explosive characteristics of buried charges when compared with open water charges. Baxter (1985) estimated that the effect of charge weight for buried charges would be less by a factor of about 5. Interestingly, the compression wave may be as much as 7 times stronger but it will decay much faster than an open water wave. The nature of the shock wave emanating from a buried charge is very complex, and models are more difficult to apply (Heathcote 1981; Baxter et al. 1982; Munday et al. 1986).

Cumulative Effects

Because oil and gas structures concentrate fishes in high numbers and those individuals tend to remain very close to the structures, explosive removal will continue to kill fishes as abandonment programs progress. Managers must view this mortality from two cumulative perspectives. The first asks how mortality from explosive platform

Table 6.3

Estimated Safe Range for Select Reef and Coastal Pelagic Species. The 10% Mortality Range is the Distance from the Detonation Point Beyond Which 90% or More of the Fishes Would Survive. Calculations are Based on Young (1991) Assuming a 23-kg (50-lb) Charge Detonated at a Depth of 15 m (50 ft) Below the Surface

Fish	Fish Weight (lbs)	Swimbladder	Safe Range (m)
Reef Species			
Red Snapper (*Lutjanus campechanus*)	5	yes	230
Sheepshead (*Archosargus probatocephalus*)	3	yes	259
Atlantic spadefish (*Chaetodipterus faber*)	2	yes	246
Lane snapper (*Lutjanus synagris*)	1	yes	310
Vermilion snapper (*Rhomboplites aurorubens*)	0.2	yes	349
Coastal Pelagic Species			
King mackerel (*Scomberomorus cavalla*)	15	no	12
Spanish mackerel (*Scomberomorus maculatus*)	3	no	12
Little tunny (*Euthynnus alletteratus*)	8	no	12

removal contributes cumulatively along with other sources of mortality such as fishing, trawl bycatch, and natural causes to fish population growth and stability. The second asks how explosive removal affects fish populations incrementally through time. Gitschlag et al. (2000) addressed the first question for populations of red snapper in the Gulf of Mexico. By including platform removal mortality estimates with other sources of mortality (fishing, natural, and trawl bycatch) used in stock assessment calculations, they concluded that mortality of red snapper from platform removal did not adversely affect red snapper populations in the Gulf of Mexico.

The second cumulative perspective was also discussed by Gitschlag et al. (2000). Long-term projections about the significance of platform removal on red snapper populations in the Gulf of Mexico will ultimately depend upon the importance of the platforms as habitat for certain species. Gitschlag et al. (2000) estimated that 66,435 red snapper would be killed each year by explosive removals from about 129 platforms. The incremental effects over time could certainly have a cumulative effect on red snapper populations and other federally managed fish populations if platforms prove to be critical habitat in portions of the Gulf of Mexico.

Similar issues should be considered for the Pacific OCS Region, where cumulative effects on populations of relatively long-lived rockfish species could be more detrimental to local populations.

6.2 Marine Turtles

6.2.1 Physical Effects of Underwater Explosions

The effects of an underwater explosion on pelagic marine vertebrates such as marine turtles are dependent upon several factors: the size, type, and depth of the explosive charge; the size and depth of the turtle in the water column; overall water column depth; and the standoff distance from the explosive charge to the turtle (Department of the Navy 2001). Impacts to marine turtles are a result of physiological responses (generally the destruction of tissues at air-fluid interfaces) to both the type and strength of acoustic signature and shockwave generated by the underwater explosion.

Generally, blast injury, defined as biophysical and pathophysiological events and the clinical syndromes that occur when a living body is exposed to a blast of any origin, comprises two categories: primary blast injury (PBI) and cavitation (Department of the Navy 2001). PBI occurs when the blast wave strikes and compresses the body, and energy from the blast is transferred directly from the transmitting medium (air or water) to the body surface. Injury resulting from PBI is almost totally limited to gas-containing organs: in marine turtles, this would be primarily the auditory system and lungs (Geraci and St. Aubin 1985). Cavitation occurs when compression waves generated by an underwater explosion propagate to the surface and are reflected back through the water column as rarefaction waves. The rarefaction waves, subsequently, create a state of tension within the water column, causing cavitation (defined as the formation of partial vacuums in a liquid by high intensity sound waves) within a bounded area called the cavitation region. The direct effects of cavitation on marine turtles is unknown, though (as in the case of marine mammals) it is assumed that the presence of a turtle within the cavitation region created by the detonation of a small charge could directly annoy or injure the animal (primarily the auditory system or lungs) or increase the severity of PBI injuries to the animal (Department of the Navy 2001).

Quantitative data concerning direct effects of underwater explosions on marine turtles are virtually nonexistent, consisting of observational information collected during one study (Klima et al. 1988), as discussed later in **Section 6.2.2**. Therefore, a discussion of the effects of explosions on these animals must be inferred from documented effects to other marine vertebrates with lungs or other gas-containing organs, such as mammals. The range of potential impacts to marine turtles has been divided into three categories: non-injurious effects; non-lethal injuries; and lethal injuries.

Non-injurious Effects

Non-injurious effects of underwater explosions to marine turtles include acoustic annoyance and mild tactile detection or physical discomfort.

Acoustic Annoyance

The anatomy of the ear of marine turtles is discussed in a general way to serve as the basis for an analysis of the processes of sound reception in these animals. As in mammals, most reptiles demonstrate three principal divisions of the ear: the outer ear, the middle ear, and the inner ear. The outer ear receives sound waves from the external environment. In turtles, the external ear is entirely absent (Wever 1978). However, the sound-receptive and conductive mechanism of the middle ear is well developed (Hadžiselimović and Andelić 1967; Wever 1978). Typically, the middle ear of reptiles consists of a tympanic membrane, or tympanum, and an ossicular chain, comprising the columella and extracolumella, suspended in an air space (the tympanic cavity) and leading inward to the oval window to the inner ear. The tympanic cavity is connected with the throat (pharynx) by a Eustachian tube. In marine turtles, there is no tympanic membrane *per se*, but the function of such a membrane is served by a tympanum composed of layers of superficial tissues at the side of the head that are no more than a continuation of facial tissue over a depression in the skull that forms the middle ear cavity (Wever 1978; Lenhardt et al. 1985; Bartol et al. 1999; Bartol and Musick 2003). The outer layer consists of a heavy fibrous plate with a thin, scale-like surface. The middle layer is particularly thick and contains a large amount of fatty tissue embedded in a delicate fibrous network, a feature that distinguishes them from both terrestrial and semiaquatic turtle species (Moein 1994). Collectively, the thick tympanum does not inhibit overall sound reception, but rather acts as additional mass loading to the ear, allowing for reduction in the sensitivity of sound frequencies and increasing low-frequency, bone conduction sensitivity (Lenhardt et al. 1985; Bartol et al. 1999; Bartol and Musick 2003).

Electrophysiological studies to determine the acoustic sensitivity of green turtle (*Chelonia mydas*) and loggerhead turtle (*Caretta caretta*) using auditory brainstem response (ABR) techniques found that the effective range of hearing of these species is within low frequencies (100 to 500 Hz) (Ridgway et al. 1969, 1970; Lenhardt et al. 1994; Moein 1994; Moein et al. 1994; Bartol et al. 1999; Bartol and Ketten 2003). Lenhardt et al. (1983) and Moein et al. (1993, 1994) found that bone-conducted hearing appears to be an effective reception mechanism for marine turtles (loggerhead and Kemp's ridley [*Lepidochelys kempii*]), with both the skull and shell acting as receiving surfaces for water-borne sound at frequencies encompassing the 250 to 1,000 Hz range. As high sound frequencies are attenuated by bone, the range of bone conducted sounds detected by marine turtles are limited to only low frequencies (Tonndorf 1972).

These data suggest that marine turtle auditory perception occurs through a combination of both bone and water conduction rather than air conduction (Lenhardt 1982; Lenhardt and Harkins 1983).

From these studies, it is reasonable to assume that the marine turtle auditory apparatus is sensitive to sounds produced by underwater explosions, and the air-filled middle ear, or tympanic cavity, is sensitive to associated pressure effects. It may be presumed that detonations of low intensity or of sufficient distance to be detected but not injurious could result in a momentary startle response or perhaps temporary disorientation of a marine turtle.

Tactile Detection or Physical Discomfort

Data pertaining to the tactile perception of marine turtles from an explosive shock wave are not available. It is reasonable to assume that marine turtle skin in soft tissue areas, particularly areas around the eyes, mouth, external nares, and vent, are sensitive to tactile stimulation. Based on studies conducted on human subjects, reports of tactile perception associated with low-level or distant underwater detonations range from the sensation of pressure, to "stings" of varying degree (moderate or strong) when exposed to shock waves (Department of the Navy 2001). It is expected that marine turtles may also experience similar sensations when exposed to low intensity or distant explosive shock waves. However, the tactile perception of marine turtles to explosive shock waves within this range of intensity would be of such brevity that it would be expected to cause at most a momentary startle response. If exposed to stronger shock waves, strong tactile responses (moderate to strong stings) would likely occur along with injuries to their auditory system and other internal organs.

Injuries

Non-lethal Injuries

Non-lethal injuries include "minor" injuries to the turtle's auditory system and certain internal organs. It should be noted that delayed complications arising from individual or cumulative non-lethal injuries may ultimately result in the death of an affected marine turtle.

The most sensitive organ to the primary effects of a blast wave is the auditory apparatus (Office of the Surgeon General 1991). The rupture of the tympanic membrane, or the tympanum in the case of marine turtles, while not necessarily a serious or life-threatening injury, correlates to permanent hearing loss (Ketten 1995, 1998). No data exist which correlate the sensitivity of the marine turtle tympanum and middle and inner ear to trauma associated with shock waves associated with underwater explosions.

Other slight injuries include those to internal organs. These include slight lung hemorrhage and contusions (defined as injury to tissue, usually without laceration [such as bruising]), and hemorrhage of the gastrointestinal tract caused by excitation of radial oscillations of small gas bubbles normally present in the intestine (Richmond et al. 1973; Yelverton et al. 1973). Goertner (1982) developed a conservative model for calculating the ranges for occurrence of these two types of internal organ injuries to marine mammals when exposed to underwater explosion shock waves. This model by itself is probably not applicable to marine turtles, as it is not known what degree of protection to internal organs from shock waves is provided to marine turtles by their shell. The general principals of the model, however, may be applicable. For lung hemorrhage, the Goertner model considers lung volume as a function of animal weight (mass) and depth, and considers shock wave duration and impulse tolerance also as a function of animal weight and depth. Injuries to the gastrointestinal tract, however, could be related to the magnitude of the peak shock wave pressure over the hydrostatic pressure, which, according to the Goertner model, is independent of animal size and weight.

Overall, non-lethal injuries associated with underwater explosions, such as the onset of lung hemorrhage and gastrointestinal tract contusion, are injuries from which a marine turtle would be expected to recover on its own and would not be debilitating (Department of the Navy 2001).

Lethal Injuries

Lethal Injuries to Internal Organs

Lethal injuries may result from massive trauma or combined trauma to internal organs as a direct result of proximity of the affected turtle to the point(s) of detonation. Extensive lung hemorrhage is an injury that all marine mammals or turtles would not be expected to survive (Department of the Navy 2001). This discussion draws from observations made on mammals subjected to underwater explosions. Gastrointestinal tract injuries associated with the onset of extensive lung hemorrhage are shown to include contusions with no ulcerations (defined as a break or disintegration of the surface tissue) (Richmond et al. 1973). As the severity of the lung hemorrhage increases, gastrointestinal tract injuries would be expected to include contusions with ulcerations throughout the tract, ultimately including ruptures of the tract. Mortality associated with these combined severe injuries is expected to be almost certain. As described in the Department of the Navy (2001) analysis of impacts of underwater explosions on marine mammals, the onset of extensive lung hemorrhage may also be used as a conservative index for the onset of mortality of marine turtles of any size class.

Lethal Injuries from Shock Waves with High Peak Pressure

Exposure of animals to high peak pressure shock waves may result in concussive brain damage, cranial, skeletal (or shell) fractures, hemorrhage, or massive inner ear trauma (Ketten 1995). Depending upon the size of the animal (with smaller animals being more susceptible), extremely high shock wave pressure impulse levels may or may not be lethally injurious to the animal's internal organs. However, overall system shock and significant external tissue damage as well as severe localized damage to the skeletal system would be expected. These injuries, if not themselves fatal, would probably put the animal at increased risk of predation, secondary infection, or disease (Department of the Navy 2001).

6.2.2 Observations of Marine Turtles Injured or Killed by Underwater Explosives

Three unidentified marine turtles were unintentionally exposed to three underwater detonation tests carried out by the Naval Coastal Systems Center off Panama City, Florida in 1981 (O'Keeffe and Young 1984). Each test detonated a mid-water charge equivalent of 1,200 lb (544 kg) of TNT in water of about 120 ft (37 m) depth. Three unidentified marine turtles were noted subsequent to the detonations. The first, a 400 lb (182 kg) animal, was killed at a distance of 500 to 700 ft (152 to 213 m) from the charge. The second, a 200 to 300 lb animal, received non-lethal, minor injuries at a range of 1,200 ft (366 m) from the charge. The third, another 200 to 300 lb animal, was apparently unaffected at a range of 2,000 ft (610 m) from the charge. Turtle depths at the time of detonation are unknown. Assuming these animals were at a mid-water depth of 60 ft (18 m) at the time of the detonation, calculated shock wave pressures are 239, 161, 85, and 47 psi (35, 23, 12, and 7 kPa) at ranges of 500, 700, 1,200, and 2,000 ft (152, 213, 366, and 610 m), respectively (Department of the Navy 2001). A summary of the effects of underwater explosions on marine turtles, as reported by O'Keeffe and Young (1984) and Klima et al. (1988), is presented in **Table 6.4** (from Department of the Navy 2001).

Evidence of the potential effects of explosive removal of offshore structures on protected species first became apparent in March and April 1986 when 51 marine turtles, primarily Kemp's ridley, and 41 bottlenose dolphin (*Tursiops truncatus*) were found dead on Texas beaches shortly after the explosive removal of oil and gas structures in Texas state waters of the Gulf of Mexico that involved 22 underwater explosions (Klima et al. 1988; NRC 1996). Because commercial shrimp trawling operations (a major cause of marine turtle mortality) were at a very low level in the area, these mortalities were attributed to explosions associated with these structure removals (though this was never verified) (Klima et al. 1988).

In July 1986, an unidentified dead or injured turtle drifting in an inverted attitude about 10 ft below the surface was sighted 1.5 hours after an explosive removal of an offshore platform off Sabine Pass, Texas (Gitschlag and Renaud 1989).

After a 1987 explosive platform removal, two turtles (both loggerheads) that were found stranded on nearby beaches were autopsied. One turtle showed no characteristics consistent with explosive impacts. External inspection of the second turtle revealed a bloated carcass with green-colored flesh and evidence of gas bubbles below the shell scutes. Necropsy results showed lung hemorrhage, four ruptures of the right atrium, and bloody fluid in the pericardial sac. Though lung hemorrhage is consistent with impacts resulting from underwater explosions, this condition, along with ruptures in the heart, may also have been the result of postmortem decomposition (Klima et al. 1988).

At a removal site of a caisson in 1991, a loggerhead with a fracture down the length of its carapace surfaced within 1 minute of detonation (NRC 1996).

Two immature green turtles were killed when 20 lb (9.1 kg) of plastic explosives (C-4) were detonated in open water (at distances of 100 to 150 ft [30.5 to 45.7 m] from the charge) by a U.S. Navy Ordnance Disposal Team. Necropsy examinations revealed extensive internal damages, particularly to the lungs (NRC 1996). Overall water depth, charge depth, and turtle depths were not reported. Turtle body mass also was not reported, although it is assumed to be small, considering the turtles were reported as of

Table 6.4

Underwater Explosion Effects on Marine Turtles Reported by O'Keeffe and Young (1984) and Klima et al. (1988)
(From: Department of the Navy 2001)

Charge Weight lbs (kg)	Charge Depth ft (m)	Water Depth ft (m)	Turtle Weight lbs (kg)	Turtle Depth ft (m)	Range ft (m)	Peak Pressure psi (kPa)	Injuries: Immediate	Injuries: 1-hr after blast
O'Keeffe and Young (1984)								
1,200[1] (544)	60 (18.3)	120 (36.6)	400 (181)	Unknown	500-700 (152-213)	258-178 (1,758-1,213)[2]	Mortal injury	---
1,200[1] (544)	60 (18.3)	120 (36.6)	200-300 (91-136)	Unknown	1,200 (366)	99 (675)[2]	Minor injury	---
1,200[1] (544)	60 (18.3)	120 (36.6)	200-300 (91-136)	Unknown	2,000 (610)	57 (388)[2]	None	---
Klima et al. (1988)								
203[2] (92)	14.8 (4.5)[3]	29.5 (9.5)	14.8 (6.7)	14.8 (4.5)	750 (229)	16.3 (111)[3]	Unconscious	Vasodilation around throat and flippers (lasted 2-3 wks); 2 cm of cloacal lining everted
203[2] (92)	14.8 (4.5)[3]	29.5 (9.5)	9.3 (4.2)	14.8 (4.5)	750 (229)	16.3 (111)[3]	Unconscious	As above and including redness around eyes and nose
203[2] (92)	14.8 (4.5)[3]	29.5 (9.5)	1.3 (0.6)	14.8 (4.5)	1,200 (366)	10.3 (70)[3]	Unconscious	Appeared normal
203[2] (92)	14.8 (4.5)[3]	29.5 (9.5)	12.1 (5.5)	14.8 (4.5)	1,200 (366)	10.3 (70)[3]	Unconscious	Normal behavior, but vasodilation around base of flippers (lasted 2-3 wks)
203[2] (92)	14.8 (4.5)[3]	29.5 (9.5)	2.9 (1.3)	14.8 (4.5)	1,800 (549)	6.5 (44)[3]	None visible	Appeared normal
203[2] (92)	14.8 (4.5)[3]	29.5 (9.5)	8.8 (4.0)	14.8 (4.5)	1,800 (549)	6.5 (44)[3]	None visible	Appeared normal except for vasodilation around throat and flippers (lasted 2-3 wks)

Table 6.4. Underwater Explosion Effects on Marine Turtles Reported by O'Keeffe and Young (1984) and Klima et al. (1988) (From: Department of the Navy 2001) (continued).

Charge Weight lbs (kg)	Charge Depth ft (m)	Water Depth ft (m)	Turtle Weight lbs (kg)	Turtle Depth ft (m)	Range ft (m)	Peak Pressure psi (kPa)	Injuries	
							Immediate	1-hr after blast
203[2] (92)	14.8 (4.5)[3]	29.5 (9.5)	3.3 (1.5)	14.8 (4.5)	3,000 (915)	4.1 (28)[3]	None visible	Appeared normal
203[2] (92)	14.8 (4.5)[3]	29.5 (9.5)	15.0 (6.8)	14.8 (4.5)	3,000 (915)	4.1 (28)[3]	Unconscious	Appeared normal except for vasodilation around throat and flippers (lasted 2-3 wks)

[1] TNT equivalent.
[2] Four 50.75-lb (23-kg) nitromethane charges buried 16.4 ft (5 m) below the mudline.
[3] Calculations for buried charges assumed a 2-lb (0.92-kg) TNT charge detonated "free-field" at mid-depth in the water column.

"immature" size class. In an open water environment, 20 lb (9.1 kg) of C-4 explosive, as used in this event, would be expected to generate nominal peak pressures of 347 and 244 psi (2,394 and 1,684 kPa) at ranges of 100 and 150 ft (30.5 and 45.7 m), respectively (Department of the Navy 2001).

Klima et al. (1988) placed four Kemp's ridley and four loggerhead turtles in cages at four distances (750 ft [213 m], 1,200 ft [366 m], 1,800 ft [549 m] and 3,000 ft [915 m]) from an offshore platform scheduled for removal using explosive charges. The cages were suspended at a depth of 15 ft (4.5 m) over a seafloor of 30 ft (9 m) depth prior to the simultaneous detonation of four, 50.75 lb (23 kg) charges of nitromethane, placed inside the platform's support pilings at a depth of 16 ft (5 m) below the seafloor ("mudline"). The Kemps ridleys and loggerheads exposed at 750 ft and 1,200 ft, as well as one loggerhead exposed at 3,000 ft, were rendered unconscious. The Kemps ridleys exposed at 750 ft also sustained slight physical injury, showing an eversion of cloacal lining through its vent. Remaining Kemps ridleys at more distant ranges were apparently unharmed. All loggerheads displayed abnormal pink coloration of soft tissues around the eyes and external nares, and at the base of the throat and flippers, reportedly caused by a dilation of blood vessels. This condition persisted in these individuals for a period of 2 to 3 weeks.

Unfortunately, data collected by Klima et al. (1988) did not include concurrent pressure measurements to estimate the magnitude and duration of the shockwave received by the caged turtles. Peak shock wave pressures for buried charges such as those used in this platform removal may be as low as 10% of expected free-field values for non-buried charges (Connor 1990). Ranges and estimated pressures for this data set were used to calculate an equivalent "non-buried" charge weight, using standard similitude equations and weak shock theory (Gaspin 1983). From these data, a 2 lb (0.92 kg) TNT charge detonated free-field would produce the shock wave pressures at the ranges shown in **Table 6.4**. Since the water depth of this platform removal was extremely shallow (30 ft [9 m]), multiple shock wave pulses and bulk cavitation resulting from bottom- and surface-reflected shock waves could have impacted the turtles.

6.3 Marine Mammals

This section reviews and discusses the definition of impacts of underwater explosions from the perspective of the NEPA and what constitutes a "significant" impact on marine mammals. In addition, it addresses the potential for "takes" of marine mammals as defined in the MMPA, as amended in 1994 (16 CFR §1431 *et seq.*). A "take" is the equivalent of an impact under the MMPA.

The following section begins with a brief description of the hearing abilities of marine mammals, followed by a discussion of the mechanisms by which shock waves generated by underwater explosions affect marine mammals. The following types of potential effects of explosives on marine mammals are then discussed:

- Changes in behavior and distribution of the animals (this definition is currently under discussion for inclusion in the revised MMPA);
- Temporary reduction in hearing sensitivity evident as TTS;
- Permanent hearing impairment or damage to hearing organs evident as permanent threshold shift (PTS); and
- Mortality or physical injury other than to hearing organs.

This discussion is followed by an analysis of the criteria used to determine level of impact due to explosives and other pulsed noises, as accepted by NOAA-F (formerly NMFS) within the context of the MMPA. The section concludes with sections on mitigation and monitoring and data gaps and recommendations for research.

6.3.1 Zones of Influence

A series of zones of potential influence of generally decreasing size can be defined for any particular sound. The zone within which the received level from an explosive in at least one part of the frequency spectrum exceeds both the ambient level and the absolute hearing threshold for a particular marine mammal species (at that frequency) is often large. This is the zone of audibility. However, the zones within which there is the potential for disturbance or displacement, and especially auditory impairment or injury, will be much smaller (**Figure 6.2**). The maximum possible zone of influence is the distance beyond which its received level falls substantially below the ambient noise level or the hearing threshold in all frequency bands. Once the noise falls substantially below ambient or below the hearing threshold, marine animals will not be able to detect sound generated by the explosive. Ambient noise levels vary dramatically over time and season and among geographic areas. Thus, the radius of the zone of detection is also highly variable.

TTS is the lowest level of physical damage. Brief exposures to loud sounds can temporarily increase the hearing threshold of an animal. This effect is temporary and largely reversible. Prolonged exposure to continuous intense sounds can cause permanent hearing damage (PTS). TTS is an important criterion of effect because it can be and sometimes is used as a safety criterion: exposure to levels below the TTS threshold will not cause physical damage, but may cause disturbance in some species. Exposure to progressively higher levels causes increased risk of physical harm. In the case of underwater explosives, these progress from mild recoverable damage to the lungs and other organs to death.

6.3.2 Hearing in Marine Mammals

Hearing in Toothed Whales (Odontocetes)

Behavioral audiograms have been reported for a small number of species of small- to moderate-sized odontocetes, and a partial audiogram is available for the Risso’s dolphin (Nachtigall et al. 1995). Based on this research, it is evident that the odontocetes tested to date hear sounds over a wide range of frequencies.

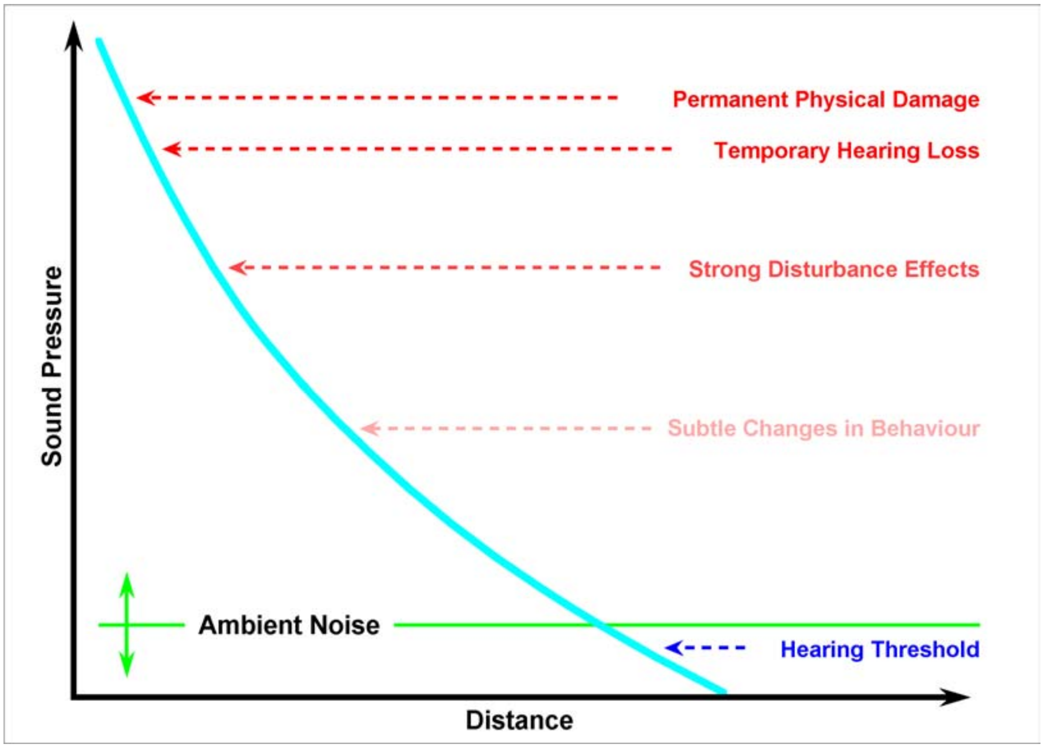

Figure 6.2. Schematic representation of the zones of potential influence of anthropogenic sounds on marine mammals. Note that the vertical distances among the different effects are not drawn to scale (Adapted from: Richardson et al. 1995).

These odontocetes hear best at frequencies of 20 kHz and above. At lower frequencies, their hearing thresholds increase (deteriorate) with decreasing frequency. Below the frequency range of optimum sensitivity, thresholds increase gradually with decreasing frequency. However, estimated auditory thresholds for many species may be inaccurate, and possibly too high, for frequencies below 1 to 10 kHz. The relatively small sizes of the holding tanks used for most hearing tests cause confounding complications, including echoes, standing waves, elevated noise levels, and nearby pressure release boundaries (Cummings et al. 1975).

Hearing ability extends at least as low as 40 to 75 Hz in the bottlenose dolphin (**Figure 6.3**), one of the species whose sensitivity at low frequencies has been reported in detail (Johnson 1967). However, the hearing sensitivity of small-medium odontocetes at these low frequencies seems quite poor. The thresholds of a Pacific white-sided dolphin have also been shown to deteriorate at low frequencies (**Figure 6.3**; Tremel et al. 1998).

In contrast, the high-frequency hearing abilities of most small- to medium-sized odontocetes are exceptionally good, and are related to these cetaceans' use of high-frequency sound for echolocation. The hearing range extends up to 80 to 150 kHz

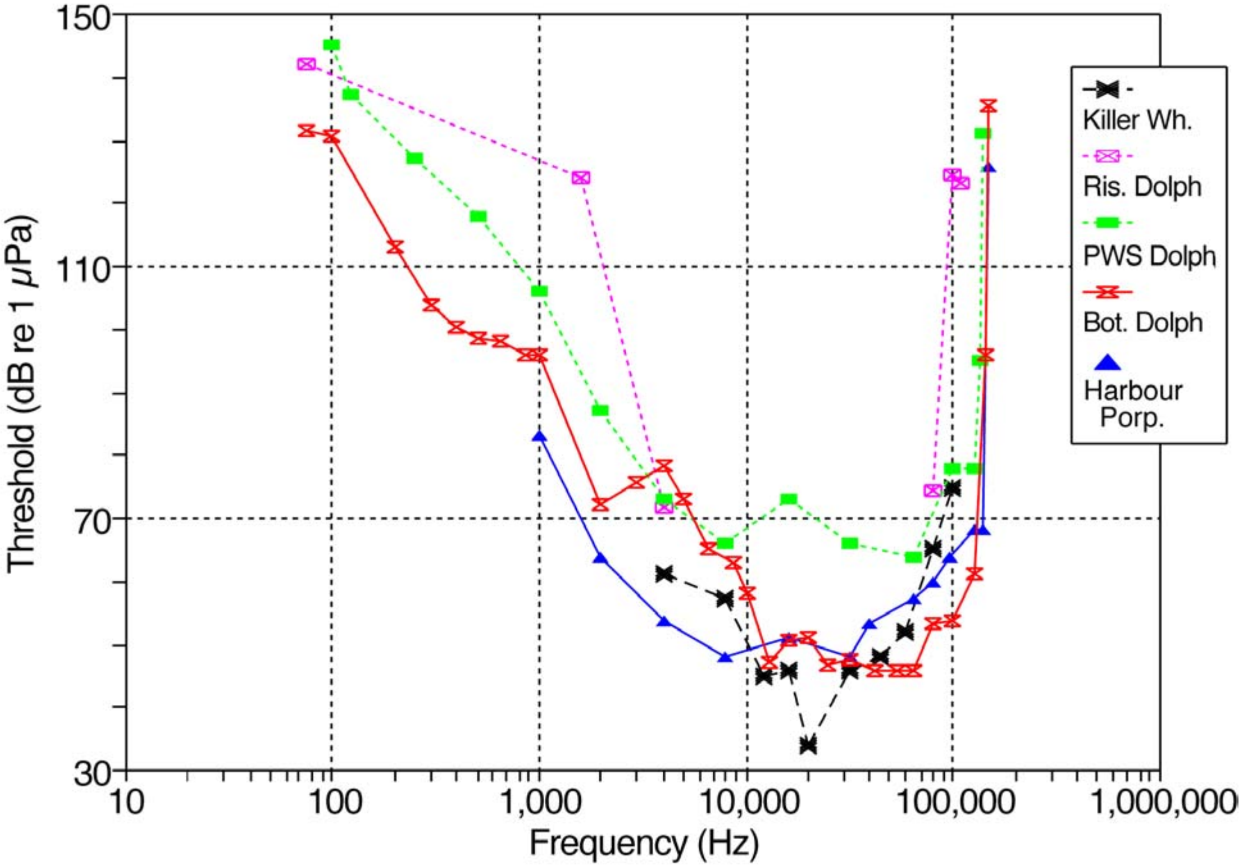

Figure 6.3. Underwater audiograms of selected toothed whale species, showing the minimum detectable sound level for tonal sounds at various frequencies. Based on killer whale data of Szymanski et al. (1999), Pacific white-sided dolphin data of Tremel et al. (1999), bottlenose dolphin data of Johnson (1968), Risso's dolphin data of Nachtigall et al. (1995, 1996), and harbour porpoise data of Andersen (1970).

in at least some individuals of all of the species tested to date. New data from other killer whales show upper frequency limits near 120 kHz, consistent with other small-medium sized odontocetes (Szymanski et al. 1999).

Within the range of "middle" frequencies where odontocetes have their best sensitivity, their hearing is very acute. When there was little background noise, the killer whale tested by Hall and Johnson (1972) could detect a 15-kHz signal of ~30 dB, a very low value. Except for the higher (~62 dB) threshold of the Pacific white-sided dolphin, the minimum thresholds were ~42-55 dB for two additional odontocete species shown in **Figure 6.3**. Overall, the frequencies at which these three species had best sensitivity ranged from ~8 to 90 kHz (**Figure 6.3**). The best sensitivity of the Risso's dolphin could not be determined (Nachtigall et al. 1995).

The most sensitive frequency in the mean killer whale audiogram was 20 kHz (36 dB), a frequency lower than that for other reported odontocetes; much spectral energy has been reported for wild killer whale clicks at or near this frequency (Szymanski et al. 1999). Killer whales reliably responded to 100 kHz tones presented at 95 dB. Verboom (2000) has suggested that this indicates that the absolute hearing threshold of larger odontocetes is lower than that of the smaller species; this generalization has yet to be demonstrated, given the lack of hearing data for many odontocete species.

The only information on the hearing abilities of sperm whales comes from a single ABR[1] study of a sperm whale neonate that was stranded in Texas during September 1989. Carder and Ridgway (1990) recorded neural responses to experimental pulses presented at rates of 20 to 40 pulses per second. The calf's ABR waves in response to pulses ranging in peak frequency from 2.5 to 60 kHz appeared to be similar to those reported for other mammals, and very similar to those observed in other odontocetes (Carder and Ridgway 1990). The ABRs of highest amplitude were those to frequencies of 5, 10, and 20 kHz, although there were weaker responses to 60 kHz tones. Low-frequency hearing was not tested.

These data suggest that, at least for immature animals, sperm whales may have medium- and high-frequency hearing abilities similar to other smaller odontocete species tested to date. Whether this is true for adult sperm whales is unknown, and their absolute hearing thresholds are also unknown. Sperm whales often react (by becoming silent) when exposed to pulsed sounds at frequencies ranging from a few kHz up to at least 24 kHz (Richardson et al. 1995).

We are aware of no published data on the hearing abilities of *Mesoplodon* (beaked) or *Hyperoodon* (bottlenose) odontocete species. Anecdotal accounts of the northern bottlenose whale's (*H. ampullatus*) response to sounds of low intensity (during quiet periods) suggests that they are able to hear sounds of low amplitude (Hooker 1999). Echolocation clicks with components from 2 to 24 kHz were recorded while bottlenose whales were diving in a deep canyon on the NW Atlantic continental shelf (Hooker 1999), and clicks of lower frequency were heard while these whales were at the surface. While this suggests that this species can hear sounds ranging in frequency from 2 to 24 kHz, the recording system was unable to sample frequencies above 35 kHz (Hooker 1999). Further studies are required to determine the full range of bottlenose and beaked whale vocalizations and to measure the relationship between sound frequency and sensitivity for this, and other, large odontocetes.

Hearing Abilities of Baleen Whales (Mysticetes)

Due to their large size and the consequent difficulties in maintaining them in captivity, the hearing abilities of mysticete whales have not been studied directly using behavioral or AEP methods.

[1] Electrical brain activity is detected using electrodes attached harmlessly to the skin of the whale as sounds are played to the marine mammal; this is an auditory evoked potential (AEP) method.

The available data on low-frequency hearing suggest that in odontocetes and pinnipeds, as in terrestrial mammals, sensitivity deteriorates with decreasing frequency below the "best" frequency. This is probably, in part, an adaptation to the typically high levels of natural underwater noise at low frequencies. However, it is not known how closely mysticetes follow this trend. They are known to emit low-frequency sounds. That, plus the anatomy of their auditory organs (Ketten 2000), suggests that mysticete whales have good low-frequency hearing.

Behavioral evidence indicates that mysticetes hear very well at frequencies below 1 kHz (Richardson et al. 1995). Mysticete whales have also been observed to react to sonar sounds at 3.1 kHz and other sources centered at 4 kHz. Some mysticetes react to pinger sounds up to 28 kHz, but not to pingers or sonars emitting sounds at 36 kHz or above (Watkins 1986).

Some mysticetes produce sounds at frequencies up to 8 kHz, although their calls are predominantly at low frequencies, mainly below 1 kHz (see Chapter 7 in Richardson et al. 1995). Based on this, plus the aforementioned anatomical evidence, it is presumed that their hearing abilities are good at low frequencies. The auditory system of mysticete whales is almost certainly more sensitive to low-frequency sounds than is the auditory system of the small- to moderate-sized odontocete whales. Mysticetes are known to detect the low-frequency sound pulses emitted by seismic airguns and change their direction of movement (e.g., Richardson et al. 1986; Miller et al. 1999; McCauley et al. 2000) or change their calling behavior (Greene et al. 1999).

Based on this indirect field and anatomical evidence, we can probably assume that mysticete whale hearing is similar at frequencies ranging from <1 to 8 kHz, and then deteriorates with increasing frequency. Ambient noise energy in the ocean is higher at low frequencies than at mid-frequencies. At frequencies in the 1 to 8 kHz range, ambient noise levels occurring under the quietest natural conditions (and in the absence of manmade sound) are rarely less than 60 dB on a 1/3rd octave basis, i.e., in bands roughly approximating the filter bandwidth of the mammalian ear (Richardson et al. 1995). It is unlikely that mammals would have evolved a hearing system able to hear sounds much lower than the weakest masking noise that would ever be encountered. We might therefore expect that the hearing threshold for mysticete whales is about 50 dB at their best frequencies. Sensitivity probably deteriorates at higher frequencies. It probably also deteriorates slowly with diminishing frequency below 1 kHz, in parallel with the lowest levels of natural ambient noise (on a 1/3rd octave basis).

6.3.3 Mechanisms of Injury

High explosive detonations have a velocity of detonation of 5,000 to 10,000 m per second (Urick 1975; Parrott 1991; Demarchi et al. 1998). Because of this, they have very short rise times of about 20 microseconds and short pulse durations of about 0.2 to 0.5 milliseconds. After the initial positive shock pulse that causes pressure to increase, pressure falls below ambient pressure and then rises to a second maximum known as the first bubble pulse. The time between the shock and the first bubble pulse is 0.17 to

0.5 seconds, depending on the size of the explosive (Demarchi et al. 1998). Effective broadband source levels for high explosive charges of 0.5 to 20 kg are on the order of 267 to 280 dB re 1 μPa at nominal 1-m distance (Richardson et al. 1995).

There are two mechanisms of injury. The very rapid rise time of the shock wave causes much damage. The sharp rise in pressure is followed by a negative pressure wave generated by the collapsing bubble. A series of decreasing positive and negative pressure pulses follow the main pulse. Marine mammals are designed to withstand changes in pressure. A human can dive to a depth of 30 m and ascend to the surface again in 10 minutes. However, an instantaneous change in depth from 0 to 30 m and back to 0 m would have catastrophic effects on humans and marine mammals.

Shock waves can cause minor or severe injury or mortality, depending on the intensity of the shock wave and size and depth of the animal (Yelverton et al. 1973; Craig and Hearn 1998; Craig 2001). The most severe damage takes place at boundaries between tissues of different density. Different velocities are imparted to tissues of different densities, and this can lead to their physical disruption. Blast effects are greatest at the gas-liquid interface (Landsberg 2000). Gas-containing organs, particularly the lungs and gastrointestinal tract, are especially susceptible (Yelverton et al. 1973; Hill 1978; Goertner 1982). Lung injuries, including laceration and rupture of the alveoli and blood vessels, can lead to hemorrhage, creation of air embolisms, and breathing difficulties. In addition, gas-containing organs including the nasal sacs, larynx, pharynx, trachea, and lungs may be damaged by compression/expansion caused by the oscillations of the blast gas bubble (Reidenberg and Laitman 2003).

Intestinal walls can bruise or rupture, with subsequent hemorrhage and escape of gut contents into the body cavity. Less severe gastrointestinal tract injuries include contusions, slight hemorrhaging, and petichia (Yelverton et al. 1973).

Ketten et al. (2003) and Reidenberg and Laitman (2003) exposed dead marine mammals to underwater blasts. Damage was consistent with what would be expected in live animals and included apparent hemorrhages at the blubber-muscle interface and in gas-containing organs and the gastrointestinal tract; ruptures of the liver and spleen; and contusions of the kidney. The blubber, melon, and jaw fats have distinct damage patterns (Ketten et al. 2003). The density and, hence, sound speed velocity in these tissues are different from those of adjoining tissues. In humans, compression of the thorax and abdomen by the shock wave would cause rapid increase in venous pressure in the brain, leading to rupture of small blood vessels, petechial hemorrhage, and oedema (Landsberg 2000). Compression also appears to cause air to enter tissues adjacent to air spaces in dead marine mammals exposed to explosives (Reidenberg and Laitman 2003). The rapid decompression during the negative bubble pulse could cause air embolism in humans (Landsberg 2000).

Because they are the most sensitive to pressure, the ears are the organs most sensitive to injury (Ketten 2000). Ketten (1995, 1998, 2000) has described the hearing organs of marine mammals. The external ears are occluded and end in a blind pouch that does not contact the middle ear. In odontocetes, sound is transmitted by fatty sound channels and bone in the jaw. The fluid-filled middle ear contains the tympanic membrane and the ossicle bones. The tympanic membrane has no direct contact with the water. The inner ear contains the spiraled cochlea and balance organs. Hair cells in the cochlea transmit sound to the auditory nerves. The basilar membrane is a main part of the cochlea. Its shape, stiffness, thickness and mass determine an animal's hearing abilities. Severe damage to the ears includes tympanic membrane rupture, fracture of the ossicles, damage to the cochlea, hemorrhage, and cerebrospinal fluid leakage into the middle ear. Moderate injury implies partial loss of hearing due to tympanic membrane rupture and blood in the middle ear. Permanent hearing loss also can occur when the hair cells are damaged by loud noises caused by one very loud event, prolonged exposure to a loud noise, or chronic exposure to noise. The latter type of injury was common among factory workers and soldiers, especially artillery men, prior to the advent of hearing protection guidelines and mandatory use of hearing protection.

Single airguns used in seismic exploration produce pulses with rise times slower that those of high explosives. Rise time for airgun pulses are on the order of 1 millisecond, the initial positive pulse is of about 2 milliseconds duration, and the following pulse is about 3 to 5 milliseconds in duration (Parrott 1991). In addition, during seismic exploration, airguns are fired several times per minute for periods of days or weeks. There is a great deal of literature on the effects of shock waves produced by airguns used for seismic exploration on marine mammals and other marine life. However, because the nature of shock waves produced by high explosives and airguns is very different, much of the literature on effects of seismic pulses cannot be used to estimate physical effects of explosives on marine mammals.

6.3.4 Review of the Documented Effects of Explosives on Marine Mammals

There is a great deal of literature on the potential and some on the observed effects of explosives on marine mammals, but very little quantitative data on the impulses needed to cause various kinds of effects, and those that do exist are based on experiments with terrestrial animals. Most of the data are qualitative in nature. This section will deal with documented cases of effects of underwater explosions on marine mammals, and the following section will deal with blast injury models that have been developed to predict potential impacts.

Effects on Behavior and Distribution

Behavioral reactions of marine mammals to a sound are difficult to predict. Reactions to sound, if any, depend on species, state of maturity, experience, current activity, reproductive state, time of day, weather, and many other factors. If a marine mammal does react to an underwater sound by changing its behavior or moving a small distance, the impacts of the change may not be significant to the individual, the stock, or the species as a whole. On the other hand, if a sound source displaces marine mammals from an important feeding or breeding area for a prolonged period, impacts on the animals could be significant.

There is relatively little information on effects of explosives on marine mammal behavior. Therefore, we also have included information on effects of seismic exploration on behavior, recognizing that the nature of shock waves produced by high explosives and airguns is very different.

Gray whales exposed to noise from explosives "were seemingly unaffected and in fact were not even frightened from the area" (Fitch and Young 1948); no other information was given. Payne and McVay (1971), studying humpback whales, stated that "loud sounds in the ocean, for example dynamite blasts, do not seem to affect the whale's songs." Payne (1970) presented a recording of a humpback that continued to sing through the noise from two distant explosions. Lien et al. (1993) found that humpbacks remained in an area where there were repeated large underwater detonations; whales that were observed directly during detonations apparently did not show obvious behavioral reactions. Some of these humpbacks may have been close enough to the blast site to suffer hearing damage or other physical injuries (Ketten et al. 1993; Ketten 1995).

During the 1950's, small explosive charges were dropped into an Alaskan river in attempts to scare belugas away from salmon. Success was limited (Fish and Vania 1971; Frost et al. 1984). Small explosive charges were "not always effective" in moving bottlenose dolphins away from sites in the Gulf of Mexico where larger demolition blasts were about to occur (Klima et al. 1988). Odontocetes may be attracted to fishes killed by explosions, and thus attracted rather than repelled by "scare" charges. Hence, scare charges are now not used in the Gulf of Mexico platform removal program (G.R. Gitschlag pers. comm. 1994, in Richardson et al. 1995). Captive false killer whales showed no obvious reaction to single noise pulses from small (10 g) charges; the received level was ~185 dB re 1 μPa (Akamatsu et al. 1993).

"Seal bombs" have a source level of about 190 dB re 1 μPa (Jefferson and Curry 1994). Jefferson and Curry (1994) reviewed studies of the effects of these on marine mammals and found that they were largely ineffective. They did not keep harbor seals and several species of fur seal out of an area, especially when fishes were in that area. The seals either habituated or returned. Off Alaska, seal bombs, blasting caps, and even dynamite were ineffective in keeping killer whales away from longlines. Explosives have also been unsuccessful in keeping bottlenose dolphins off Africa, Dall's porpoise in the North Pacific, and dolphins in the Mediterranean Sea away from fishing gear (Jefferson and Curry 1994).

Seal bombs were, until recently, widely used to influence the movements of the dolphins around which purse-seine nets are set during tuna fishing operations in the eastern Pacific Ocean (Cassano et al. 1990; Myrick et al. 1990a,b). The charges were thrown within meters of the dolphins in attempts to divert them onto a different heading. One method of fishing involved the use of seal bombs thrown from helicopters and speedboats at and around schools of dolphins (Glass 1989). The dolphins would slow down and become confused. They would then form a protective school. As the mile long net was being set, seal bombs were used to keep dolphins and tuna from escaping through the open side. U.S. regulations now prohibit the use of seal bombs in the tuna-dolphin fishery.

Finneran et al. (2000) exposed trained captive bottlenose dolphins and beluga whales to single simulated sounds of distant explosions. Broadband received sound levels were 170 to 221 dB re 1 μPa (p-p; 155 to 206 dB rms). Maximum spectral density was about 102 to 142 dB re 1 $\mu Pa^2/Hz$ at a 6.1 Hz bandwidth. Pulse durations were 5.4 to 13 ms. Behavioral alterations began at 196 to 209 dB (p-p; 181 to 194 dB rms; 120 to 127dB re 1 $\mu Pa^2/Hz$). Although pulse durations for the two studies were different, the sound levels required to induce disturbance appear to have been similar to those found by Ridgway et al. (1997) and Schlundt et al. (2000). Behavioral alterations were departures from trained behaviors to the stimuli and included swimming around the enclosure rather than travelling directly between stations, vocalizing, refusing to return to a station, and remaining on a station.

More specific information about the reactions of some baleen and odontocete whales to low-frequency noise pulses has been obtained by observing their responses to pulses from airguns and other non-explosive methods of marine seismic exploration. Bowhead whales on their summering grounds in the Beaufort Sea (Richardson et al. 1986), migrating gray whales off California (Malme et al. 1983, 1984), and migrating or lingering humpback whales off Western Australia (McCauley et al. 1998, 2000) all showed clear avoidance reactions to seismic sounds at received levels of about 160 to 170 dB re 1 μPa (rms) and, in some cases, somewhat lower levels. Humpback whales showed avoidance at a mean received sound level of 140 dB re 1μPa rms. About 50% of feeding gray whales will cease feeding at an average peak pressure level of 173 dB (Malme et al. 1988), and about 50% of migrating gray whales will avoid a seismic source at the about the same average received sound levels (Malme and Miles 1985).

Behavioral changes have sometimes been evident at somewhat lower received levels. Migrating bowheads avoided an active seismic survey boat at received sound of 116 to 135 dB, but avoidance did not persist for more than 12 to 24 h after cessation of operations (Miller et al. 1999; Richardson et al. 1999). These avoidance reactions occurred at much lower average received levels than the average of 160 to 170 dB needed to elicit responses on their summering grounds.

There is some recent evidence that sperm whales may cease calling when exposed to weak noise pulses from extremely distant (>300 km) seismic exploration (Bowles et al. 1994) and that they may, perhaps, move away from a seismic vessel (Mate et al. 1994). The observed avoidance reactions involved movement away from feeding locations or statistically significant deviations in the whales' direction of swimming and/or migration corridor as they approached or passed the sound sources. In the case of the migrating whales, the observed changes in behavior appeared to be of little or no biological consequence to the animals—they simply avoided the sound source by displacing their migration route to varying degrees, but within the natural boundaries of the migration corridors. As noted above, seismic pulses are usually emitted several times per minute for days or weeks at a time.

Common dolphins avoid the localized area around active seismic vessels and may tolerate sounds at distances of 1 km or more from the array (Goold 1996; Goold and Fish 1998). The proportion of all small cetaceans sighted during seismic shooting in UK waters was reduced within given ranges of large arrays (Stone 2003). There was no difference in the sighting rates of large cetaceans. Behavior of whales was different between periods when airguns were active and when they were not shooting (Stone 2003). When guns were active, there was less bow-riding, fewer approaches to the vessel, and fewer instances of swimming alongside, following, or close ahead of the vessel and more alterations of course away from the vessel. In some instances, reaction to the airgun sounds was species-specific. There also was less evidence of feeding activity when airguns were operating. Behavior during a soft start or ramp up was about midway between fully operational and no guns firing. As in the case of baleen whales, avoidance was temporary (Stone 2003).

Sperm whales apparently reacted to seismic sounds at a distance of about 20 km where received sound levels were 146 dB re 1 μPa (p-p) or 124 dB re1 μPa^2 (Madsen et al. 2002).

In general, there seems to be a great deal of variability in the reactions to low frequency pulsed sounds among species. A given species may react differently depending on the time of year and their activity. Single or a few pulses may not have much of an evident behavioral effect, and single very loud pulses may have no effect on some species when they are feeding. Effects of single loud pulses may have only a transitory affect on behavior.

Temporary Threshold Shift (TTS)

TTS is the mildest form of hearing damage that occurs during exposure to a strong sound (Kryter 1985). TTS is the process whereby exposure to a strong sound results in a non-permanent elevation of the minimum hearing sensitivity threshold (Kryter 1985). TTS can last from minutes or hours to days. The magnitude of TTS depends on the level and duration of noise exposure, among other considerations (Ward 1997). While experiencing TTS, a sound must be louder to be heard. For sound exposures at or somewhat above the TTS threshold, hearing sensitivity recovers rapidly after exposure to the noise ends.

Only a few data on sound levels and durations necessary to elicit mild TTS have been obtained for marine mammals. TTS studies in humans and terrestrial mammals provide helpful information, but it is unclear to what extent these data can be extrapolated to marine mammals.

Exposure to a sound can be expressed in terms of energy expressed in terms of dB re 1 μPa^2-s. Energy considers the intensity and duration of a sound. A sound of low intensity and long duration can contain the same amount of energy as a short sound of high intensity. Different researchers used different exposure times sound intensities, so the TTS data discussed below have been standardized in terms of energy.

Ridgway et al. (1997) exposed bottlenose dolphins exposed to 1-sec tones. Schlundt et al. (2000) expanded on this study to measure masked underwater hearing thresholds in five bottlenose dolphins and two beluga whales before and immediately after exposure to intense 1-sec tones at 0.4, 3, 10, 20, and 75 kHz. TTSs of 6 dB or larger were observed after exposure to between 192 and 201 dB re 1 μPa. The exceptions occurred at 75 kHz, where one dolphin exhibited TTS after exposure at 182 dB re 1 μPa and the other dolphin did not show any shift after exposure to maximum levels of 193 dB re 1 μPa, and at 0.4 kHz, where no subjects exhibited shifts upon exposure to levels up to 193 dB re 1 μPa. At the conclusion of the study, all thresholds had returned to baseline values, so there was no evidence of PTS.

Au et al. (1999) exposed captive bottlenose dolphins to 30 to 50 minutes of octave-band continuous noise in the 5 to 10 kHz band. Hearing was not affected when the noise level was 171 dB re 1 μPa (energy flux density of 205 dB re 1 μPa^2-s). Moderately strong TTS of 12 to 18 dB was obtained when the noise level was 179 dB re 1 μPa (energy flux density 213 dB re 1 μPa^2-s).

Kastak et al. (1999) induced mild TTS in California sea lions, harbor seals, and northern elephant seals by exposing them to underwater octave-band noise at frequencies in the 100 to 2,000 Hz range for 20 to 22 minutes. TTS of 4.8 dB became evident when the received levels were 161 to 196 dB re 1 μPa^2-s. Exposure was not continuous because the animals rose to the surface to breathe. All recovered to baseline hearing sensitivity within 24 hr of exposure

Nachtigall et al. (2003) exposed bottlenose dolphins to noise with peak amplitude at 4 to 11 kHz for 55 minutes. The test animals experienced an average TTS of 11 dB on exposure to 179 dB re 1 μPa (213 dB re 1 μPa^2-s). Recovery from the TTS was complete after 45 minutes.

Finneran et al. (2000) exposed two bottlenose dolphins and a beluga whale to broadband sounds resembling that of distant underwater explosions. The intensity and duration of the pulses were not sufficient to cause TTS, defined as a threshold shift equal to or greater to 6 dB. A bottlenose dolphin showed a TS of 5.6 dB when exposed to energy of 177 dB re 1 μPa^2-s, and a white whale showed TS of 4 dB after exposure to energy of 179 dB. The waveform produced by the piezoelectric transducers lacked energy in the lower part of the spectrum, which contains most of the energy generated by explosives. Finneran et al. (2002) exposed a bottlenose dolphin and a white whale to sounds from a seismic water gun that produced most of its energy at frequencies below 1 kHz but contained substantial energy up to 40 kHz and above. The white whale sustained TTS of 7 dB at a received energy level of 186 dB re 1 μPa^2-s. Most of the animals exposed in these experiments did not sustain TTS. Results of these studies are summarized in **Figure 6.4**.

TTS may be related to several variables, including

- Intensity of sound;
- Pulse duration;
- Amount of TS; and perhaps
- Recovery time.

Figure 6.4 shows exposure in terms of energy and duration of the exposure, but does not consider amount of TTS. Thus some of the variability shown in **Figure 6.4** can be explained by the differential amount of TS that was experienced by the test animals. On average, the animals tested by Schlundt experienced TTS of 9.5 dB. TS experienced by Finneran et al.'s (2000, 2002) and Kastak et al.'s (1999) animals was lower than 6 dB. The dolphin in Au et al.'s (1999) test experienced >12 dB of TTS.

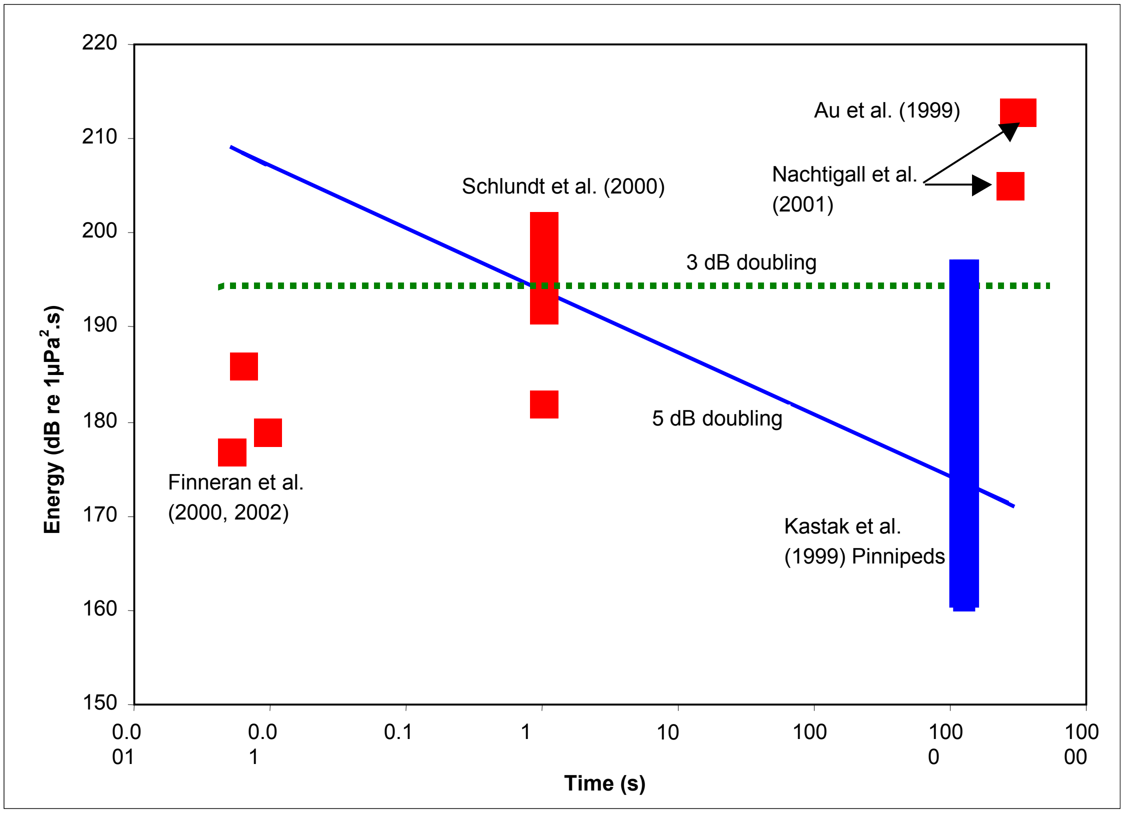

Figure 6.4. Energy levels (dB re 1 μPa^2-s) of underwater sound that have resulted in temporary threshold shift in odontocetes (red squares) and pinnipeds (blue rectangle). Data are expressed as energy (dB re 1 μPa^2-s). Data from Au et al. (1999), Kastak et al. (1999), Schlundt et al. (2000), Finneran et al. (2000, 2002), and Nachtigall (2003). Also plotted are the 5 and 3 dB exchange rates converted to energy. Energy values were estimated as per Finneran et al. (2000).

There are two options for allowing for the effect of pulse duration:

- The equal energy or 3 dB exchange rate, where the rms sound pressure level required to cause TTS increases by 3 dB for every doubling of the pulse duration; and
- The more conservative 5 dB exchange rate, where the rms sound pressure level required to cause TTS increases by 5 dB for every doubling of the pulse duration.

Figure 6.5 shows the relationship between average energy to which the odontocetes tested in the experiments described above were exposed and the average amount of TS they experienced. There appears to be a linear relationship between the amount of TS and the amount of energy to which an odontocete is exposed.

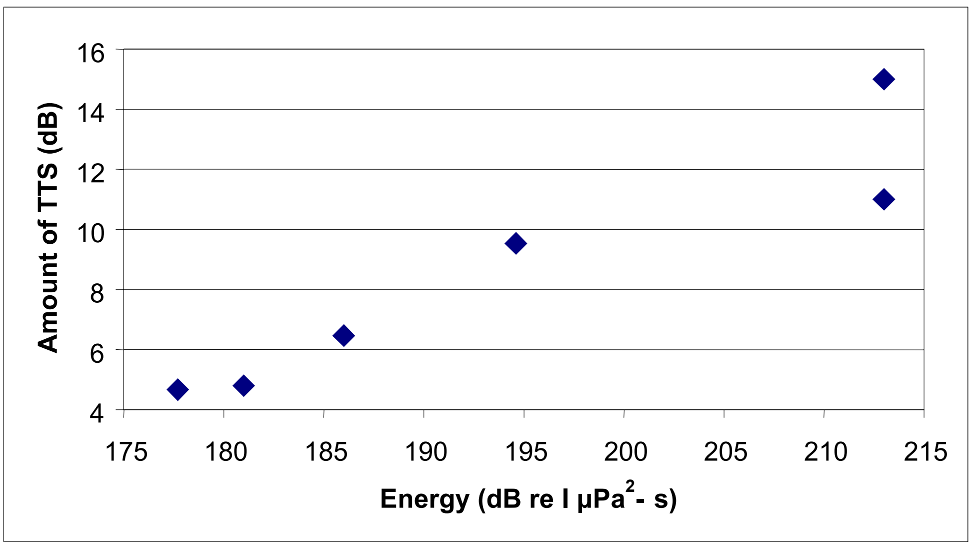

Figure 6.5. Average threshold shift experienced by and average amount of energy to which bottlenose dolphins and white whales were exposed in the experiments described in the text.

Allowing for the differential in TS experienced by the animals shown in **Figure 6.5**, the data in **Figure 6.4** seem to fit the 3 dB exchange rate (equal energy). For a single exposure, an equal amount of energy is required to cause TTS regardless of the duration of the exposure. Frequency may also be unimportant. These results are consistent with evidence from terrestrial mammals in that TTS thresholds in the dolphins were not related strongly to the frequency of the sound. TTS has been defined as a TS of 6 dB or more (Finneran et al. 2000). In the tests described above, this amount of TTS was associated with an energy level of about 184 dB re 1 μPa^2-s (**Figure 6.4**). Finneran (2003) concluded that data are few and caution needs to be used when interpreting them and applying them to impulsive sounds with high peak pressures or different waveforms. Two criteria should be used.

The Department of the Navy (2001), Helweg et al. (1998), and Sigurdson et al. (2001) estimated that TTS would occur under two different criteria, one based on energy and the other on peak pressure. Helweg et al. (1998) and Sigurdson et al. (2001) only had access to the Ridgway et al. (1997) data that were also used by Schlundt and not the remainder of the TTS data mentioned above. Those early data showed that average TTS of 9.5 dB was induced by 1-s tones at 192 to 201 dB rms. They used 192 dB rms as a conservative estimate for TTS and estimated the energy that induced TTS for brief tonal signals to be 182 dB re 1 μPa^2-s at a conservative pulse duration of 100 ms (Sigurdson et al. 2001). The energy was reference to 1/3 octave bands because human and dolphin cochlea can be modeled as a bank of 1/3 octave filters (Sigurdson et al. 2001). TTS was assumed to be induced if the received energy in any 1/3 octave band was greater than 182 dB re 1 μPa^2-s. Total broadband energy in all 1/3 octave bands would be about 193 dB re 1 μPa^2-s.

The new data show that TTS induced by broadband noise and noise from tones, including low frequency noise, fall within the same range (**Figures 6.4** and **6.5**) and that TTS of 9.5 dB is induced at 195 dB re 1 μPa^2-s (**Figure 6.5**). Broadband received levels at 200 m from a 3 kg charge would be 195 dB re1 μPa^2-s and 184 dB in the 1/3 octave band centered at 400 Hz (the octave band containing the highest energy). Thus the new data do not contradict the criteria used by Department of the Navy (2001) and accepted by NMFS (2001).

Assuming that the time of arrival of the surface cutoff wave for a 3 kg blast at 200 m distance is 14 ms (computed according to Yelverton 1981), received broadband total energy would be about 195 dB re 1 μPa^2-s. This would equate to about 213.5 dB rms and 216.5 dB peak pressure or about 9.7 psi peak pressure.

The second criteria for TTS used by the Department of the Navy (2001) and accepted by NMFS (2001) is that TTS is deemed to occur at received peak sound pressure of 12 psi. This criteria is based on a model created by Ketten (1995), which she derived through examination of ear trauma studies and models of the effect of blast over pressure on the structure of the ear. The 12 psi criteria was also accepted by NMFS (2001). For these explosions, the distance to each criterion was to be computed and the most conservative was to be used.

In the Seawolf and DDG 81 ship shock test EISs (Department of the Navy 1998, 2001), harassment was defined as the TTS criterion, which is the safe outer limit for recoverable auditory damage. TTS was assumed to be induced if energy was greater than 182 dB re 1 μPa^2-s within any 1/3 octave band or peak pressure exceeded 12 psi. Their procedure for calculating critical distances for TTS was as follows:

- Calculate the energy density spectrum for the waveform;
- Note the peak pressure in the waveform and compare it to the 12 psi criterion;
- Integrate the spectrum in 1/3 octave bands;

- Determine if the energy density in any 1/3 octave band exceeds 182 dB re 1 μPa ^{2}-s (considering frequency ranges of ≥100 Hz for toothed whales and ≥10 Hz for baleen whales); and
- Determine the shortest distance at which either of these energy criteria is exceeded for various sound speed profiles.

Multiple Exposures

A practical approach to assessing impacts of multiple exposures might be the "equal-energy" criterion of NIOSH (1998). This is conservative in the sense that the assumed impact definition does not account for recovery. It has the great advantage of readily allowing for the varying energy content of pulses received at different times, distances, and positions relative to the axis of a sonar beam. It also provides a way to deal with an animal simultaneously exposed to pulses from more than one source or to continuous sounds and pulsed sounds at the same time.

Exposure to pulsed sounds with a low duty cycle is expected to result in a reduced TTS threshold relative to a continuous exposure because, at least in humans, there may be some recovery between pulses (Ward 1997). The relationship between number of pulses and reduction in TTS threshold is unlikely to be linear or simple. For intermittent sounds of varying intensity, TTS in humans is not a constant function of total energy received, but is related to the temporal distribution of the received energy (Ward 1997). The reduction in damage is greater with short pulses and long inter-pulse intervals. The duration of the pulse appears to be more important than the inter-pulse interval in determining the amount of damage sustained (Ward 1991, 1997). Schlundt et al. (2000) found that recovery from TTS of 6 to 17 dB induced by a single 1 second pulse occurred after about 5 to 16 min. In terrestrial animals, recovery from large amounts of TTS takes hours or days (Ward 1970). In terrestrial animals, if the inter-pulse interval is short, the amount of TTS induced is a linear function of the number of pulses (combined total time of the pulses (Ward et al. 1961; Ward 1997). There are too few data to determine a metric for correcting for number of pulses, duration of pulse, and inter-pulse interval in humans (Ward 1991; NIOSH 1998). The 3 dB equivalent energy correction is a conservative way of accounting for multiple pulses (Ward 1991). Thus, when assessing TTS for animals potentially exposed to multiple shots, it would be prudent to add the energy from all shots. Thus, a 25 kg charge would result in received energy levels at 100 m distance of 204 dB re 1 μPa ^{2}-s. Four such shots would result in received energy levels of 210 dB re 1 μPa ^{2}-s [204 dB re 1 μPa ^{2}-s + 10Log(4 shots)].

Permanent Threshold Shift and Hearing Damage (PTS)

When there is physical damage to the sound receptors in the ear there can be total or partial deafness, while in other cases, the animal is unable to hear sounds at specific frequency ranges. Physical damage to a marine mammal's hearing apparatus can occur if it is exposed to sound impulses that have high peak pressures, especially if they have very short rise times. Such damage can result in permanent decrease in functional sensitivity of the hearing system at some or all frequencies. This permanent increase in the threshold above which the mammal can detect sound is termed PTS.

Single or occasional occurrences of mild TTS do not cause permanent auditory damage in terrestrial mammals, and presumably do not do so in marine mammals. Very prolonged exposure to noise strong enough to elicit TTS, or shorter-term exposure to noise levels well above the TTS threshold, can cause PTS. Sound impulse duration, peak amplitude, and rise time are the main factors thought to determine the onset and extent of PTS. Based on existing data, Ketten (1995) has noted that the criteria for differentiating the sound pressure levels that result in PTS (or TTS) are location- and species-specific. PTS effects may also be influenced strongly by the health of the receiver's ear.

At least in terrestrial mammals, the received sound level from a single noise exposure must be far above the TTS threshold for there to be any risk of PTS, i.e., permanent hearing damage (Kryter 1985, 1994; Richardson et al. 1995). Relationships between TTS and PTS thresholds have not been studied in marine mammals but are assumed to be similar to those in humans and other terrestrial mammals.

Lien et al. (1993) found that humpback whales remained in an area where there were repeated large underwater detonations. Two beached humpbacks had damaged auditory organs, consistent with the types of damage caused by explosions (Ketten et al. 1993). It is not known how close they may have been to the explosions.

Bohne et al. (1985, 1986) found that the inner ears of 5 of 11 Weddell seals that they examined showed evidence of previous damage. The type of damage observed was consistent with exposure to high noise levels. Numerous explosive charges had been detonated in the area the previous summer. There was suspicion but no proof that the auditory damage was caused by those explosions.

In humans, PTS can be induced by a single short exposure at very high level or by repeated longer exposures at moderate level (Ward 1997). There is no clear relationship between PTS, TTS, and cochlear damage (NIOSH 1998). In humans, hearing loss with increasing age is an accumulation of PTS and TTS over time (Ward 1997). Morphological studies of the ears of older dolphins showed the same kinds of changes that were associated with hearing loss in humans (Gisner 1998). Sharp rise times, such as those produced by explosions, induce PTS at lower intensities than do other types of sounds (Gisner 1998).

Damage to hair cells in the ear has been associated with hearing loss in fishes (Gisner 1998; McCauley et al. 2000). In fishes, there is some regeneration of hair cells over time, but it is unknown whether this leads to complete recovery of hearing capabilities.

Ketten (1995) estimated that >50% PTS would occur at peak pressures of 237 to 248 dB re 1 μPa and TTS at peak pressures of 211 to 220 dB for explosives (units converted by Cavanagh 2000). To avoid physical injury from explosives, Ketten (1995) recommends a safe peak pressure level of 100 psi (237 dB re 1 μPa ≈ 212 dB re 1 μPa^2-s). PTS will be assumed to occur at a received sound level of 30 dB greater than that inducing TTS. Studies of TTS in terrestrial mammals have shown TTSs of 40 dB and larger are associated with the loss of sensory hair cells (e.g., Ahroon et al. 1996). Animals can recover from smaller amounts of TTS.

Mortality or Physical Injury

Intense shock waves, because of their high peak pressures and rapid changes in pressure, can cause mortality or severe damage to marine mammals. The most severe damage takes place at boundaries between tissues of different density. Different velocities are imparted to tissues of different densities, and this can lead to their physical disruption. Gas-containing organs, particularly the lungs and gastrointestinal tract, are especially susceptible (Yelverton et al. 1973; Hill 1978; Goertner 1982).

Only a few published accounts are available pertinent to non-auditory damage to marine mammals exposed to blast. These accounts, while providing no information about the strengths of blasts that did and did not cause damage, include the following:

- Fitch and Young (1948) reported that, on at least three occasions, California sea lions were killed during seismic exploration using high explosives. In contrast, gray whales "in the region of a blast were seemingly unaffected." Unfortunately, the distances from the explosives, numbers of mammals affected and unaffected, and the sizes and positions of the charges were not stated, and necropsies apparently were not done. Charges in use during the study usually consisted of either 18 to 36 kg of high explosive detonated "a few feet" underwater, or 9 kg detonated in the bottom sediment.
- Reiter (1981) reported without further details that there was evidence of northern fur seals and birds killed from concussion in the immediate area of demolition when a grounded ship was broken up by about 454 kg of explosive. Again, numbers and distances are unknown.
- Northern fur seals have been killed by an 11.4-kg dynamite charge exploded 23 m away (H.F. Hanson 1954; cited in Wright 1982).
- Chinese river dolphins, Irrawaddy dolphins, finless porpoises, and dugongs have been killed by explosions, usually involving the use of sticks of dynamite to catch fishes (Leatherwood and Reeves 1989; Zhou and Xingduan 1991; Baird et al. 1994).
- In the Gulf of Mexico, dolphins are often seen near obsolete oil industry platforms scheduled for explosive removal (Klima et al. 1988). Demolition blasts are delayed when dolphins are within 915 m, and no confirmed blast injuries or mortality have been reported.

The auditory effects of the "seal bombs" thrown near dolphins during some tuna fishing have not been reported. An M-80 containing 3 g of explosive killed a human diver when it exploded 15 to 30 cm from his head (Hirsch and Ommaya 1972). It broke both eardrums, caused herniation of brain tissue and fracture of cranial bones. Based partly on tests with dolphin cadavers, Myrick et al. (1990a) concluded that a 4-g seal bomb will cause injury when detonated within 1.6 m of a dolphin and slight injury within 3.2 m. They estimated a safe standoff distance of 8 m. However, Cassano et al. (1990) were unable to find a relationship between the use of seal bombs in the tuna fishery and increased mortality of dolphins.

Anderson and Løken (1968) experimented on submerged rats with 1 g tetryl charges. Lethality was increased by 200% when blasts were timed at 8 to 25 μsec apart. They obtained 30% mortality with simultaneous detonation and 55% mortality with single detonations. Charges set off within small intervals would be more dangerous because animals would be subjected to a train of impulses.

A few other reports are not directly relevant because of differences in pressure vs. time patterns (Wright and Allton 1971; Fuller and Kirkwood 1977).

Models of Effects of Explosives on Marine Mammals

Several workers have described procedures for calculating safe distances from explosions to marine mammals (Yelverton et al. 1973; Hill 1978; Yelverton 1981; Goertner 1982; Wright 1982; O'Keeffe and Young 1984; O'Keeffe 1985; Young 1991; Craig and Hearn 1998; Craig 2001). Their calculations are based on the following:

- degree of damage to various submerged land mammals at different impulse levels, as determined primarily by Yelverton et al. (1973);
- the physical dependencies of impulse on charge weight, charge depth, range, and mammal depth; and, in some cases,
- the relationship between animal weight and susceptibility to injury and death (Yelverton 1981).

Hill suggests that the original Yelverton/Hill procedure probably overestimates the zones of physical influence of shock waves on marine mammals: the respiratory adaptations of marine mammals for diving probably reduce their susceptibility to sharp pressure changes. Their auditory systems seem better protected in some ways than are those of terrestrial mammals. The thick body walls of most marine mammal groups probably also would reduce damage. Some of these assumptions may be incorrect.

The original Yelverton/Hill procedure does not allow for any relationship between susceptibility and body size. Yelverton (1981) produced new equations for computing safe distances for marine mammals that considered the animal's body mass. His equations suggest that no damage would occur to a 100-kg marine mammal exposed to impulses of 289 Pa-s or less, and to a 1,000-kg marine mammal exposed to impulses of 702 Pa-s or less. Yelverton (1981) determined that the impulse levels in Pa-s that could kill or damage mammals are as follows:

50% Mortality	ln(I) = 4.938 + 0.386 ln(M)
1% Mortality	ln(I) = 4.507 + 0.386 ln(M)
No Injuries	ln(I) = 3.888 + 0.386 ln(M)

where I = impulse in Pascal-seconds and m = body mass in kilograms. The relationships between body mass and the magnitude of impulse causing injury or death to animals at the water surface are shown in **Table 6.5**. Again, these equations are based on data from submerged terrestrial mammals, and they may overstate the severity of injuries to marine mammals adapted for life in the water. The direct applicability of the equations to large marine mammals is particularly questionable, given that the largest animals from which data are available are sheep.

Table 6.5

Impulses in Pascal-Seconds Needed to Cause Injury to Various Species of Marine Mammals at the Water Surface, According to Yelverton's (1981) Equations

Species	Weight		Injury (Impulse Pa-s)		
	lbs	kg	No Injury	1% Mortality	50% Mortality
0.2-kg marine mammal		0.2	26	49	75
Dolphin calf	27	12.2	128	238	366
Common dolphin	143	65	245	454	699
Spinner dolphin	143	65	245	454	699
Bottlenose dolphin	440	200	377	701	1,078
Risso's dolphin	660	300	441	819	1,261
Large whale	2,200	1,000	702	1,304	2,007
West Indian manatee	1,100	500	537	998	1,536

Yelverton (1981) calculated peak overpressure and impulses to the time of arrival of the first surface cutoff wave using empirically determined equations:

$$P_m = 45600\left(\frac{W^{\frac{1}{3}}}{R}\right)^{1.10}$$

$$\Theta = 0.0917\left(\frac{W^{\frac{1}{3}}}{R}\right)^{-0.168} W^{\frac{1}{3}}$$

$$t_c = \left(\sqrt{R^2 + 4D_w D_g} - R\right)/C_o$$

$$I = P_m\Theta\left[\frac{9}{11}\left(1-e^{-\frac{11t_c}{10\Theta}}\right)+1-e^{\frac{t_c}{10\Theta}}\right]$$

Where P_m = peak overpressure (kPa), Θ = time constant (msec), t_c = time of arrival of the surface cut off wave, I = impulse to cut off time (Pa-s), R = slant range (m), D_w depth of charge (m), D_g = depth of guage (animal, m), C_o =speed of sound in water (1.45 m/s), and W = charge mass (kg).

The distances to the impulses causing injuries specified in **Table 6.5** are shown in **Table 6.6**. The distances were computed using Yelverton's (1981) equations and assume a 22.7 kg charge at 50 m and the animal at the surface. This model is simplistic and should not be used. It is used here for illustration.

Table 6.6

Distances in Meters to Impulses Causing No Injury, 1% Mortality, and 50% Mortality. Impulses from **Table 6.2**. Distance Computed as per Yelverton's (1981) Equations, Assuming a 22.7 kg Charge Detonated at 50 m Depth with the Marine Mammal at the Surface

Species	Distance (m) to		
	No Injury	1% Mortality	50% Mortality
0.2 kg marine mammal	450	295	209
Dolphin calf	221	135	91
Bottlenose dolphin	128	72	46

Young (1991) presents a different set of equations, in his case to compute the safe distance for marine mammals given a depth of blast of 61 m (200 ft):

Porpoise calf	$R = 578\ W_E^{0.28}$
Porpoise adult	$R = 434\ W_E^{0.28}$
20 ft Whale	$R = 327\ W_E^{0.28}$

In these equations, R = the distance in feet from blast to the mammal, and W_E is the weight of the explosive in pounds. For a dolphin calf (12.2 kg) at the surface, the safe range from a 22.7 kg charge would be 422 m. The Yelverton (1981) equation predicts no harm to a 12.2 kg dolphin calf at an impulse of 128 Pa-s. For a dolphin calf at the surface, this impulse would occur at a distance of 219 m if it was at the surface and at 778 m if the calf was at a depth of 50 m (using the equations for estimating impulse provided by Yelverton 1981).

When the explosion is near a hard (e.g., rock) bottom, shock waves may attenuate less rapidly than in open water. Hill (1978) and Wright (1982) suggest that calculated lethal ranges or safe distances should be doubled in these circumstances to ensure a conservative safety margin.

Goertner (1982) produced a model to fit the data collected by Yelverton et al. (1973) and Richmond et al. (1973). His model considered lung volume as a function of animal weight and depth, and shock wave duration and impulse tolerance as a function of animal weight and depth. In his model, because lung volume was a reduced at depth, it was a smaller proportion of body mass so was more resistant to shock waves. His parameter for scaling lung injuries as a function of depth was:

$$I / M^{\frac{1}{3}} \rho_1^{\frac{1}{3}} \rho_o^{\frac{1}{6}}$$

where I is the impulse causing a specified damage in psi.msec, ρ_l is atmospheric pressure, and ρ_o is pressure at depth in pounds per square inch, and M is the animal mass in kilograms. The Yelverton et al. (1973) and Richmond et al. (1973) data indicate that slight lung injury would occur at 20 psi-msec (138 Pa-s) for a 40-kg animal. Atmospheric pressure was 12 psi, and hydrostatic pressure at 2 ft was 12.9 psi. These data also showed that slight injuries to the intestinal tract occurred at a peak overpressure (P_{max}) of 600 psi (4,136 kPa) and at ambient pressure (ρ_o) of 12.9 psi. The damage parameter for slight intestinal tract injuries was scaled as

$$P_{max} / \rho_o$$

Craig and Hearn (1998) and Craig (2001) used Goertner's method to determine distances to various injury levels using the lowest body mass and lowest impulses for which onset of slight lung damage, extensive lung hemorrhage, and extensive lung injury occur.

Onset of slight lung injury:

$$I = 19.7\ (M/42)^{1/3} \text{ psi-milliseconds}$$
$$I = 136\ (M/42)^{1/3} \text{ Pascal-seconds}$$

Onset of extensive lung hemorrhage (1% mortality):

$$I_{1\%} = 42.9\ (M/34)^{1/3} \text{ psi-milliseconds}$$
$$I_{1\%} = 296\ (M/34)^{1/3} \text{ Pascal-seconds}$$

Occurrence of extensive lung injury (50% mortality):

$$I_{50\%} = 84.9\ (M/42)^{1/3} \text{ psi-milliseconds}$$
$$I_{50\%} = 586\ (M/42)^{1/3} \text{ Pascal-seconds}$$

Craig and Hearn (1998) and Craig (2001) compared results of these equations to Yelverton's equations for no injury, 1% mortality, and 50% mortality and found that they were slightly more conservative than the Yelverton equations. In addition, the predicted impulses were no greater than measured impulses causing the same type of injury in laboratory tests. The above equations were used to predict the zones of no injury, 1% mortality, and 50% mortality for marine mammals in the ship shock Environmental Impact Statements (EISs) (Department of the Navy 1998, 2001).

The impulses causing injury in **Table 6.7** were computed for animals at the water surface. The Seawolf and DDG81 EISs (Department of the Navy 1998, 2001) used the impulse value associated with onset of extensive lung hemorrhage (1% mortality) for a 27-pound (12.2 kg) dolphin calf as the criteria for mortality and the impulse associated with slight recoverable lung injury as a criterion for injury. These impulse values were calculated with Craig and Hearn's (1998) and Craig's (2001) adaptation of the Goertner (1982) model. The impulse predicted to cause slight injury in a 12.2 kg dolphin calf was 90 Pa-s at the surface, and the impulse to cause 1% mortality was 210 Pa-s at the surface.

Table 6.7

Impulses Causing Various Degrees of Injury Computed According to the Method of Craig (2001)

Species	Weight		Pa-s		
	lbs	kg	Slight Injury	1% Mortality	50% Mortality
0.2-kg marine mammal	0.5	0.2	23	53	99
Dolphin calf	27	12.2	90	210	388
Common dolphin	143	65	157	367	678
Spinner dolphin	143	65	157	367	678
Bottlenose dolphin	440	200	229	534	986
Risso's dolphin	660	300	262	612	1,129
Large whale	2,200	1,000	391	914	1,686
West Indian Manatee	1,100	500	311	725	1,338

The safe range for marine mammals is slight injury to a 0.2-kg marine mammal.

Goertner (1982) assumed that damage was related to lung volume as a function of body mass. Lung volume at the surface was assumed to be 3% of body mass and decreased with increasing depth. Goertner (1982) and Craig (2001) thought that as depth increases, the lung and tissues compress and a larger impulse was required to cause damage (**Table 6.8**).

Recently the effect of depth on acoustical resonance of gas filled structures has been raised as a potential issue with respect to affects of loud noise on marine mammals. This may cause or impair gas exchange. Gisner (1998) states "*if the lung resonance changes as a function of depth then as depth changes, the frequency function for damage risk threshold will need to be adjusted*." The duration of blast impulses are too short to have this kind of effect (NOAA 2002). However, decompression type effects in marine mammals may be an issue (NOAA 2002). There is the potential for long duration high intensity sound to generate bubbles (NOAA 2002). Blast pulses are of short duration, but the rapid fluctuation between positive and negative pressures could induce bubble formation. Reidenberg and Laitman (2003) found bubbles within the tissues adjacent to air spaces of dead odontocetes exposed to underwater blasts.

Table 6.8

Impulses Required to Cause Various Levels of Injury to a Dolphin Calf and Slight Injury to a 0.2-kg Marine Mammal, as a Function of Depth (From: Craig, Pers. Comm.)

Depth		12.2 kg Dolphin Calf			0.2 kg Marine Mammal
		Slight Injury (Pa-s)	Mortality (Pa-s)		Slight Injury (Pa-s)
feet	meters		1%	50%	
0	0	90	194	389	23
3.3	1	95	206	408	24
33	10	127	278	550	33
164	50	220	481	951	56
328	100	299	650	1,285	75
656	200	413	899	1,779	105

Ongoing work by Ketten et al. (2003) and Reidenberg and Laitman (2003) shows that extensive damage can occur at the boundaries between tissues of different densities. Preliminary results of this work and the concern about bubble formation indicate that depth may not confer increased resistance to trauma or that the resistance may not be as large as once thought. It is also hoped that results of this ongoing work will validate, refine, or redefine current marine mammal injury models.

In the ship shock EISs, tympanic membrane rupture was also considered as a criterion for slight injury. Peak blast overpressures of 1,034 kPa (150 psi) are associated with 50% tympanic membrane rupture (Ketten 1998). Craig (2001) and Sigurdson et al. (2001) determined that acoustic energy proportional to P^2/t (P = pressure and t = time) may be an appropriate parameter for response of the ear to high levels of underwater noise. Based on the incidence of eardrum rupture in sheep exposed to underwater explosions by Richmond et al. (1973), Craig (2001) estimated that 50% tympanic membrane rupture would occur at an energy flux density of 1.17in-lb/in^2. This criteria is more conservative than one derived by Ketten (1995) and was used in the ship shock EISs as another criterion for injury.

The criteria for marine mammal injury were as follows:

- Mortality occurs at the range of onset of extensive lung hemorrhage (1% mortality) in a 12.2-kg dolphin calf;
- Injury occurs at the range of onset slight lung injury for a 27-pound (12.2-kg) dolphin calf, or the incidence of 50% tympanic membrane rupture (1.17 in-lb/in^2); and
- A safe range is one beyond which there could be slight lung injury to a 0.2-kg marine mammal.

Criteria and Definitions of Blast Injury Used and Accepted by NOAA-F

Impact assessment of the effects of underwater explosives on marine mammals must addresses the potential for "takes" of marine mammals as defined in the MMPA, as amended in 1994 (16 C.F.R. § 1431 et seq.).

As defined in the MMPA, the term "take" means "to harass, hunt, capture, or kill, or attempt to harass, hunt, capture, or kill any marine mammal." Under the 1994 MMPA amendments, Congress defined and divided the term "harassment" to mean "any act of pursuit, torment, or annoyance which: 1) (Level A Harassment) has the potential to injure a marine mammal or marine mammal stock in the wild; or 2) (Level B Harassment) has the potential to disturb a marine mammal or marine mammal stock in the wild by causing disruption of behavioral patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering."

Underwater explosions can kill or injure marine mammals through direct physical effects. Also, marine mammals exposed to loud sounds can experience temporary reduction in hearing sensitivity (TTS), which NOAA-F considers to be potentially significant and to constitute "take." Changes in behavior can also be considered to be "takes" under the MMPA.

NOAA-F does not consider minor and temporary behavioral responses with no likely consequences for the well-being of individual marine mammals, e.g., minor startle or alert reactions, to be biologically significant or to be considered as "takes" (*Federal Register* 61(234):64,337). In the case of single underwater explosions, minor or momentary behavioral responses are not considered to be "takes" (*Federal Register* 66(87):22,452).

For repetitive impulses (seismic pulses), NMFS (1995b) accepted TTS as the definition of the lower bound for Level A harassment for seismic sounds. Off the coast of California, the limits for TTS were set at 180 dB re 1 μPa_{rms} for mysticetes and sperm whales and at 190 dB re 1 μPa_{rms} for odontocete cetaceans and pinnipeds (NMFS 1995a). That is, these were the levels below which it was assumed there would be no harassment and above which this could not be stated with certainty. However, as of March 2000, NMFS indicated that "odontocetes also be limited to an SPL no greater than 180 dB re 1 µPa RMS" (NMFS 2000). NMFS indicated that the 190 dB value would still apply for pinnipeds. In a later determination, NMFS has defined TTS as the upper portion of the Level B harassment zone and near the lower portion of the Level A harassment zone for single underwater acoustic events such as shock testing of ships and submarines (NMFS 1999, 2001).

In 1995, NMFS ruled on the use of explosives to remove offshore oil and gas structures in the Gulf of Mexico (*Federal Register* 60(197):53,139-53,147). The radius of effect for injury was determined to be 914 m. Monitoring was required to ensure that the area was clear of marine mammals prior to detonation. There has been some advancement in knowledge of effects on marine mammals since 1995, particularly in the area of temporary threshold shift and refinements to models of underwater injury. Recent EISs and ruling by NMFS have incorporated this knowledge

Level B Harassment for Explosives

The Seawolf and Winston Churchill EISs (Department of the Navy 1998, 2001) defined Level B harassment as the onset of TTS. NMFS accepted the onset of TTS as the definition of harassment for an explosive source during the Seawolf (*Federal Register* 64(3):3,280-3,286) and Winston Churchill ship shock tests (*Federal Register* 66(87):22,450-22,467).

In the Seawolf and Winston Churchill ship shock EISs (Department of the Navy 1998, 2001), harassment was defined as the TTS criterion, which is the safe outer limit for recoverable auditory damage. TTS was assumed to be induced:

1) at energies greater than 182 dB re 1 microPascal^2-second within any 1/3 octave band. Their procedure for calculating critical distances for TTS was:
   - calculate the energy density spectrum for the waveform;
   - integrate the spectrum in 1/3 octave bands;
   - determine if the energy density in any 1/3 octave band exceeds 182 dB re 1 microPascal^2-sec (considering frequency ranges of ≥100 Hz for toothed whales and ≥10 Hz for baleen whales); and

2) if the peak pressure exceeded 12 psi for an explosive source.

The distance to each criterion was determined and the shortest distance at which either criterion is exceeded was taken to be the distance at which Level B harassment (TTS) would begin to occur.

Level A Harassment for Explosives

Department of the Navy (1998, 2001) defined Level A harassment as follows:

1) Mortality occurs at the range of onset of extensive lung hemorrhage (1% mortality) in a 12.2-kg dolphin calf; and
2) Injury occurs at the range of onset slight lung injury for a 27-pound (12.2-kg) dolphin calf, or the incidence of 50% tympanic membrane rupture.

These definitions were accepted by NMFS (2001; *Federal Register* 66(87):22,450-22,467).

Criteria for Multiple Shots

If more than one shot is to be used, then the timing between shots is a critical factor to be considered in derivation of safe distances. As shown in **Chapter 4**, timing between shots and numbers of shots used are specified so that an array effect is avoided. There are no guidelines for multiple shots. The following are suggested criteria for multiple shots used to decommission platforms in the Gulf of Mexico.

The specified 900 ms interval between shots is probably not enough time for an animal to recover from TTS or other damage. Given that recovery from TTS requires minutes to days, it may be prudent to add energy from all shots fired in 1 day to determine the TTS threshold distance.

The following approach could be used to determine distances causing injury or death for multiple shots carried out within a 24-hour period:

1) Determine the distance to onset of slight injury for a 0.2-kg marine mammal for the largest shot. Beyond this distance, there should be no damage to marine mammals from multiple shots.
2) Sum the energy of all the shots and determine the distance to onset of slight lung injury for a 12.2-kg dolphin calf. If this distance is less than that computed in 1), then use that as the distance to onset of slight lung injury; if not, use the distance computed in 1).

Summary

Charges used for well severance are detonated 4.6 m (15 ft) below the mudline. There is evidence showing that, for these kinds of charges, the blast parameters are variable – they may be reduced considerably, to a minor extent, or not reduced at all.

For charges jetted into rock, peak pressure can be reduced to 5% of that in open water and impulse by 30% (Nedwell et al. 2002). The duration of the blast wave is increased to 1 to 2 ms, and more importantly the rise time is greatly increased to the order of 1 ms. Unconfined charges have very short rise times of about 20 μs and pulse durations of about 0.2 to 0.5 ms. Rock has a much higher density and compressional wave velocity than does water. As the density and compressional velocity approach those of water, the blast wave characteristics of the substrate approach those of water, and coupling between substrate and water improves.

Charges used for well severance in the Gulf of Mexico are generally 22.7 kg, and these are set off 4.6 m below the sediment/water interface. Powell (1995) analyzed Connor's (1990) data from one rig in the Gulf of Mexico and found that the peak pressure of explosives jetted into the substrate depended more on charge weight than on burial depth. He found that that the attenuation coefficient for sediment was larger than that of water at that site. Peak pressure was reduced by 50% to 75% (Connor 1990). As the attenuation of the sediment tends to approach that of water, the reduction of peak pressure and impulse due to burial also decreases (see **Chapter 4**). Thus, at one rig in the North Sea, Nedwell et al. (2002) found no reduction in peak pressure for 45-kg charges used to sever wellheads at 3 m below the water/substrate interface. They claim that these results imply that the sediment did not act as effective confinement for the blast in that it was of comparable density to that of water.

Wright and Hopkey's (1998) equations for a safe setback or burial distances to protect fish habitat predict lower reductions of peak pressure than those found in the Gulf of Mexico by Connor (1990), but higher than the 0% reduction found in the North Sea. Their guidelines use a distance/depth sufficient to insure that the explosive bubble is contained by the sediment. The 45-kg charges buried 3 m into the substrate of the Gulf of Mexico produced a peak pressure of 100 kPa (15 psi) at a distance of about 450 m from the source (Connor 1990). According to Wright and Hopky (1998), a 5-kg charge would need to be buried at least 5 m below the unconsolidated mud/water interface to produce a peak pressure of 100 kPa at the mud/water interface 0 m from the blast site.

The evidence presented above shows that measurement of blast parameters after the fact or modeling using sediment characteristics at the specific site is the only way of determining them (see **Chapter 4**). Modeling seems of little use without site specific sediment data. Thus, for the purposes of impact assessment, the prudent assumption should be that charges used for well severance behave in the same manner and produce parameters of the same magnitude as do charges detonated on the bottom in open water.

6.4 Data Gaps and Recommended Areas of Future Research

6.4.1 Marine Fishes

The fact that underwater explosions at close range kill adult fishes with swimbladders is well established. Nevertheless, even from the limited number of platform removals that have been monitored, there was considerable variability in numbers of individuals killed relative to the estimated extant populations (G. Gitschlag, NMFS, pers. comm.). Properly designed caging experiments used during actual platform removals may shed light on the nature of this variability.

There is an appreciable gap in the knowledge about sublethal and behavioral effects of short-term exposure to high impulse sound on adult and early life stage fishes. For example, limited evidence suggests that high impulse sounds can permanently damage sensory hair cells in the middle ear of fishes (McCaulay et al. 2003). Detailed anatomical evaluations of this type of injury should be analyzed using histological techniques that would reveal possible sublethal effects. Govoni et al. (2002) demonstrated that caging studies would work on larval and early juvenile fishes. There is no information on the use (or not) of auditory cues by larvae or early juveniles of Gulf of Mexico fishes. This could be documented with field experiments using hydrophone playbacks.

6.4.2 Marine Turtles

Very little information exists regarding the effects of underwater explosions on marine turtles. The effects of explosions to humans and other terrestrial mammals, or marine mammals is not reliably extrapolated to marine turtles. It may be possible to collect supportive data concerning explosion parameters that may result in non-lethal injuries to the marine turtle auditory mechanism or other gas-filled organs by conducting tests on non-listed aquatic turtle species. Studies designed to ascertain damaging effects (nonlethal or lethal) of underwater explosions on marine turtle organs and other tissues may utilize dead marine turtles, similar to ongoing and successful studies conducted on dead marine mammals by Ketten et al. (2003).

Visual census methods (i.e., shipboard and aerial surveys) appear to provide the most reliable means to date to determine the presence of marine turtles around offshore oil and gas structures prior to explosive removals. Active underwater acoustic methods are untested, and data may be confounded by subsurface structures as well as the presence of large fishes or aggregations of fishes associated with offshore structures.

6.4.3 Marine Mammals

There are five principal kinds of knowledge required to address and mitigate impacts on marine mammals:

- Explosion parameters that cause recoverable hearing loss (TTS);
- Explosion parameters that cause onset of recoverable injury or slight trauma;
- Explosion parameters that cause permanent injury or death;
- Effects of multiple shots; and
- Detection of marine mammals with in the safety zones.

In terms of explosion parameters that cause injury, received sound levels that cause TTS are the best known. However, none of these data are based on sounds with rise times comparable to those of high explosives. We do not know if the rise time is a factor in inducing TTS. Damage risk criteria are not available for humans or terrestrial animals (Ahroon et al. 1996), so it is not possible to extrapolate from terrestrial to marine mammals.

Blast parameters causing PTS and tympanic membrane rupture are unknown, and only educated guesses are available. Blast parameters causing recoverable and permanent injury or death have been extrapolated from submerged terrestrial animals. It not known how well these data translate to effects on marine mammals, however, Ketten et al. (2003) are currently conducting this kind of research with dead marine mammals with apparent good results.

The effect of depth on blast resistance and decompression type effects require some attention. The current models assume that depth confers some protection from blast injury, but this may not be the case.

The time interval between shots may be an important mitigation measure. The amount of time for an animal to recover from a shock wave is unknown. Do closely spaced shock waves, each of which is insufficient to cause damage, cause damage in proportion to 1) the sum of all damage parameters, or 2) a sum of a time dependent percentage of damage parameters? The ship shock tests were single blasts with one or more days between shots. The effects of short time intervals between blasts such as those used in the Gulf of Mexico have not been addressed.

Detection of marine mammals in the Gulf of Mexico is complicated by the presence of animals that make long deep dives. Thus, acoustic as well as visual observations are needed to ensure that animals are not in the area. However, this method will not work for species that do not call while underwater. Not enough is known about the vocal behavior of beaked whales and some other species to determine the probability of their being detected by passive acoustical methods.

The Office of Naval Research (ONR) is conducting research on TTS, effects of blast parameters on marine mammals, and detection of marine mammals with passive acoustic devices. Synergy between MMS and ONR in these areas of research would be fruitful. The Department of the Navy, Naval Surface Warfare Center is measuring actual blast parameters in the sea and working on new and/or revisions to blast propagation models. Synergy with this group also would be fruitful.

CHAPTER 7
MITIGATION AND MONITORING

7.1 Marine Fishes

Measures used by various state agencies to mitigate planned explosions in aquatic (freshwater) settings were reviewed by Keevin (1998). The following were fundamental categories for developing mitigative strategies:

- blasting design;
- biological criteria; and
- physical mitigation features.

Keevin (1998) concluded that blasting contractors must work more closely with natural resource agencies to reduce potential adverse effects and recommended that blasting permits be required. MMS's existing platform removal permit includes aspects from each of these categories (see **Chapter 2**). Blasting design parameters that can affect the extent of fish kill associated with an underwater explosion are discussed in detail in **Chapters 3** and **4.** These include charge weight, charge type, shaped charges, and decking. Biological criteria described by Keevin (1998) were lethal range models, observers, compensation of fishery losses, pre-blast sampling surveys to detect fish presence, and seasonal restrictions on blasting that coincide with spawning, migratory, or other aggregation times. Physical mitigation strategies used in the past either seek to drive fishes away from the blast site with small charges or low frequency noise, or to lessen the severity of the shock wave with bubble curtains or physical barriers. These recommendations work well for blasting projects in inland and possibly coastal waters, but most are not applicable or economically feasible for offshore oil and gas platforms. For example, bubble curtains would certainly help reduce fish kills associated with platform removal, however, such devices would have to be fabricated for each different removal scenario. Design and development cost would be very high.

For platform removal, blasting design is affected by permit requirements. According to MMS, operators may propose any type of blasting design. If the design does not conform to one of those encompassed under the generic incidental take statement, a special consultation must occur to review the requested action. Biological criteria such as pre-blast surveys for marine mammals and turtles are required in the MMS permit. NMFS observers also may be present during removal operations to estimate the number of dead fishes floating on the surface following a detonation. When possible, NMFS personnel collect fish samples, which are identified to species, counted, and measured. However, these efforts conducted by NMFS personnel are not required under the MMS permit. As part of this requirement, numbers and kinds of fishes floating at the surface are qualitatively estimated following the detonation.

Other than the items already covered in the current MMS permit regarding blast design, benefits of mitigation and monitoring for fishes in the Gulf of Mexico and Santa

Barbara Channel would not outweigh the costs. In Cook Inlet, AK, where economically important species such as Pacific herring and salmon could occur in the vicinity of platforms, mitigation procedures should include temporal windows to avoid peak spawning/aggregation times, observers and pre-blast remote sensing to detect large aggregations of fishes, and if critical times cannot be avoided, physical barriers should be deployed.

7.2 Marine Turtles

The discovery of beached marine turtles and bottlenose dolphins following the 1986 explosive platform removal event (**Section 6.2**) prompted the initiation of formal consultation authorized through Section 7 provisions of the ESA of 1973 (16 U.S.C. 1531-1543) between two federal agencies with jurisdiction in federal waters: NMFS and MMS (Henwood 1988). The purpose of this consultation was to determine a mechanism to minimize potential impacts to listed species. Further, in consideration of MMPA, the agencies discussed the potential for unintentional (i.e., incidental) take and proposed take limits for future explosive removal activities (Richardson 1989). The consultation resulted in a requirement for oil and gas companies to obtain a permit (through separate consultations on a case-by-case basis) from the MMS prior to using explosives in federal waters. Because many offshore structure removal operations are similar, a "generic" Incidental Take Statement was established by the NMFS on 25 July 1988 that describes requirements to protect marine turtles. A summary of these requirements, as described in Richardson (1989) and Gitschlag et al. (1997), are listed in **Table 7.1**. To be considered under the "generic consultation," a proposal for an explosive structure removal had to meet the following limitations, as established by the NMFS (from Richardson 1989):

1) High velocity explosives with a detonation rate of 7,600 m/s or greater must be used;
2) Each explosive charge cannot exceed 50 lb (with a maximum 50 lb backup charge);
3) Charges must be placed a minimum of 5 m (15 ft) below the seafloor (mud line); and
4) Detonations must be limited to groups of eight or less, with a minimum of 900 ms (0.9 second) between each detonation.

Similar procedures were adopted for explosive structure removals within state waters, where permits were managed and obtained by the U.S. Army Corps of Engineers.

In 1987, the NMFS initiated a marine turtle observer program that followed the guidelines specified in the NMFS Incidental Take Statement (**Table 7.1**) at all oil and gas structure explosive removal sites in both state and federal waters of the Gulf of Mexico (Gitschlag 1990). Aerial survey techniques were found to be approximately 10 times more effective in observing marine turtles than day or night surface surveys (i.e., from vessels and from oil and gas platforms). From these studies, turtles were primarily sighted near structures positioned in water depths of 15 to 60 m (Gitschlag et al. 1997). From 1987 through 1988, surveys sighted turtles at 13% of the structures removed

(Gitschlag and Renaud 1989). Surveys conducted during 1992 and 1993 sighted marine turtles at 20% and 13% of the structures monitored, respectively (Gitschlag and Herczeg 1994; Gitschlag et al. 1997). The marine turtle observer program has been successful in mitigating impacts to marine mammals and turtles associated with the explosive removal of offshore structures. However, even with these protective measures in place, there have been observations of marine turtles impacted by explosive platform removals (**Table 7.2**) (G.R. Gitschlag 2003, pers. comm., NOAA-F, Galveston, TX).

Table 7.1

Summary of the National Marine Fisheries Service "Generic" Incidental Take Statement Regarding the Protection of Marine Turtles Prior to and During the Explosive Removal of Offshore Structures (From: Richardson 1989 and Gitschlag et al. 1997)

1)	Qualified observers must monitor the area around the site for marine turtles beginning 48 hours prior to detonations;
2)	A 30-minute aerial survey must be conducted within 1 hour prior to and after detonation;
3)	If marine turtles are observed within 1,000 yards of the structure prior to detonation, detonations must be delayed until the animals have moved beyond 1,000 yards. The aerial survey must also be repeated;
4)	Detonations must occur no sooner than 1 hour after sunrise and no later than 1 hour before sunset;
5)	During salvage-related diving, divers must report turtle and mammal sightings. If turtles are thought to be resident, pre- and post-detonation diver surveys must be conducted;
6)	Explosive charges must be staggered to minimize cumulative effects of the explosions;
7)	Avoid the use of "scare" charges to frighten away turtles that may be attracted to the point of detonation to feed on dead marine life and be subsequently exposed to explosions; and
8)	The structure removal company must file a report summarizing the results.

Table 7.2

Marine Turtles Impacted from Explosive Structure Removals from 1987 to May 2003 (From: G.R. Gitschlag 2003, Pers. Comm.)

Month	Year	Species	Observed Condition
October	1990	*Caretta caretta*	Cracked shell
November	1997	*Caretta caretta*	Cracked shell
July	1998	*Caretta caretta*	Dead from blast
August	2001	*Caretta caretta*	Stunned from blast

Note: *Caretta caretta* = loggerhead turtle.

Subsequent to the marine turtle mortalities associated with underwater detonations in 1981 (**Section 6.2.2**), O'Keeffe and Young (1984) proposed that a safe range for marine turtles from a free-field underwater explosion could be expressed by the equation $R = 200\ w^{1/3}$, where R is the safe distance, or range, in feet and w is the charge weight in pounds. This equation was later modified by Young (1991) to $R = 560\ w^{1/3}$, based on estimates of safe ranges as established by the NMFS for explosive platform removals. The metric form of this equation is $R\ (m) = 222\ W(\text{in kg})^{1/3}$. Young (1991), however, suggested that calculated marine turtle safe ranges should only be used for preliminary planning purposes. For example, applying the Young (1991) equation for safe distances to observations recorded in Klima et al. (1988), this equation predicts a safe range of 1,003 m (3,291 ft), which is slightly greater than the greatest distance at which an effect was observed (i.e., a turtle was rendered unconscious at a distance of 915 m [3,000 ft], the greatest distance tested) (Department of the Navy 2001). These results suggest that explosive impacts might be realized at distances greater than 915 m (3,000 ft); additional research is necessary to further refine models that estimate safe distances for marine turtles exposed to explosive removal operations.

Using the O'Keeffe and Young (1984) data for marine turtles, a model developed by Goertner (1982) for calculating the ranges for occurrence of two types of internal organ injury to marine mammals exposed to shock waves associated with an underwater explosion was run for the test conditions for the onset of lung hemorrhage, onset of extensive lung hemorrhage, and extensive lung hemorrhage (Department of the Navy 2001). Prediction results from this test were consistent with the mortal injury suffered by the 181-kg (400-lb) turtle located 152 to 213 m (500 to 700 ft) from the detonation, the minor injuries suffered by the 91- to 136-kg (200- to 300-lb) turtle 366 m (1,200 ft) from the detonation, and the uninjured 91- to 136-kg (200- to 300-lb) turtle 610 m (2,000 ft) from the detonation. These results suggest that lung injury predictions for marine turtles are not inconsistent with predictions for small mammals, as developed for the impact analysis of the Final EIS for the DDG 81 shock trial (Department of the Navy 2001).

Keevin and Hempen (1997) suggest that it may be possible to protect marine turtles from underwater explosions by either avoiding periods when they are in the project area or by removing the turtles from the project area. Depending on location and species, there may be time periods when certain marine turtle species are not in the project area due to life history or migration patterns, or seasonally. These periods may be determined by coordination with the state natural resource agency or NOAA-F. Theoretically, detonations may be planned during time periods of low turtle abundance. However, in areas such as the Gulf of Mexico, marine turtles are ubiquitous during all seasons except perhaps during mid-winter months when seawater temperatures are depressed. Explosive removal activities during these months rarely occur because of inclement weather conditions. As a last resort, turtles have been physically captured and removed from the project area. This method is considered inefficient and unreliable.

In 1995 and 2002, NMFS implemented monitoring and mitigation measures to reduce or eliminate the potential for impact to marine turtles and marine mammals, as detailed in the following section.

7.3 Marine Mammals

In recent years, monitoring and mitigation have been required to protect marine mammals when explosives are used in the marine environment. An LOA was issued in 1995 by NMFS for the incidental take of marine mammals during removal of oil and gas structures in the Gulf of Mexico (*Federal Register* 60(197):53,139-53,147). The following monitoring and mitigation measures were required:

(a) Observer(s) approved by the NMFS in advance of the detonation must be used to monitor the area around the site prior to, during, and after detonation of charges.

(b) (1) Both before and after each detonation episode, an aerial survey by NOAA-F-approved observers must be conducted for a period not less than 30 minutes within 1 hour of the detonation episode. To ensure that no marine mammals are within the designated 3,000 ft (1,000 yd, 941 m) safety zone nor are likely to enter the designated safety zone prior to or at the time of detonation, the pre-detonation survey must encompass all waters within 1 nmi of the structure.

(2) A second post-detonation aerial or vessel survey of the detonation site must be conducted no earlier than 48 hours and no later than 1 week after the oil and gas structure is removed, unless a systematic underwater survey, either by divers or remotely-operated vehicles, dedicated to marine mammals and sea turtles, of the site has been successfully conducted within 24 hours of the detonation event. The aerial or vessel survey must be systematic and concentrate down-current from the structure.

(3) The NOAA-F observer may waive post-detonation monitoring described in paragraph (b)(2) of this section provided no marine mammals were sighted by the observer during either the required 48 hour pre-detonation monitoring period or during the pre-detonation aerial survey.

(c) During all diving operations (working dives as required in the course of the removals), divers must be instructed to scan the subsurface areas surrounding the platform (detonation) sites for bottlenose or spotted dolphins and if marine mammals are sighted to inform either the U.S. government observer or the agent of the holder of the LOA immediately upon surfacing.

(d) (1) A report summarizing the results of structure removal activities, mitigation measures, monitoring efforts, and other information as required by an LOA, must be submitted to the Director, NOAA-F, Southeast Region, 9721 Executive Center Drive N, St. Petersburg, FL 33702 within 30 calendar days of completion of the removal of the rig.

(2) NOAA-F will accept the U.S. Government observer report as the activity report if all requirements for reporting contained in the LOA are provided to that observer before the observer's report is complete.

These requirements were updated in August 2002 (*Federal Register* 67(148):49,869-49,875). While nearly identical to the mitigation, monitoring, and reporting requirements previously issued in 1995, the 2002 requirements included several new and important additions, including

1) In water depths of 150 ft (46 m) or greater, or in cases where divers are not deployed in the course of normal removal operations, an ROV must be deployed prior to detonation to scan areas below structures. If marine mammals are sighted, the ROV operator must inform either the NMFS-approved observer or the agent of the holder of the LOA immediately; and
2) In water depths of 328 ft (100 m) or greater, passive acoustic detection must be employed prior to detonation. If marine mammals are detected by the acoustic device, the operator must inform either the U.S. government observer or the agent of the holder of the LOA immediately.

An LOA was issued in 1999 and 2001 for the U.S. Navy's ship shock tests. Monitoring was required during the Seawolf ship shock test *(Federal Register* 64(3):3,280-3,286) and the Winston Churchill ship shock test (*Federal Register* 66(87):22,450-22,467). The following monitoring with respect to marine mammals was required for the Winston Churchill test.

"(a) The holder of the Letter of Authorization is required to cooperate with the National Marine Fisheries Service and any other Federal, state or local agency monitoring the impacts of the activity on marine mammals. The holder must notify the appropriate Regional Director at least 2 weeks prior to activities involving the detonation of explosives in order to satisfy paragraph (f) of this section.

(b) The holder of the Letter of Authorization must designate qualified on-site individuals, as specified in the Letter of Authorization, to record the effects of explosives detonation on marine mammals that inhabit the Atlantic Ocean test area.

(c) The test area must be surveyed by marine mammal biologists and other trained individuals, and the marine mammal populations monitored, 48-72 hours prior to a scheduled detonation, on the day of detonation, and for a period of time specified in the Letter of Authorization after each detonation. Monitoring shall include, but not necessarily be limited to, aerial and acoustic surveillance sufficient to ensure that no marine mammals are within the designated safety zone nor are likely to enter the designated safety zone prior to or at the time of detonation.

(d) Under the direction of a certified marine mammal veterinarian, examination and recovery of any dead or injured marine mammals will be conducted. Necropsies will be performed and tissue samples taken from any dead animals. After completion of the necropsy, animals not retained for shoreside examination will be tagged and returned to the sea. The occurrence of live marine mammals will also be documented.

(e) Activities related to the monitoring described in paragraphs (c) and (d) of this section, or in the Letter of Authorization issued under § 216.106, including the retention of marine mammals, may be conducted without the need for a separate scientific research permit. The use of retained marine mammals for scientific research other than shoreside examination must be authorized pursuant to subpart D of this part.

(f) In coordination and compliance with appropriate Navy regulations, at its discretion, the National Marine Fisheries Service may place an observer on any ship or aircraft involved in marine mammal reconnaissance, or monitoring either prior to, during, or after explosives detonation in order to monitor the impact on marine mammals.

(g) A final report must be submitted to the Director, Office of Protected Resources, no later than 120 days after completion of shock testing the USS Winston S. Churchill. This report must contain the following information:

(1) Date and time of all detonations conducted under the Letter of Authorization.

(2) A description of all pre-detonation and post-detonation activities related to mitigating and monitoring the effects of explosives detonation on marine mammal populations.

(3) Results of the monitoring program, including numbers by species/stock of any marine mammals noted injured or killed as a result of the detonation and numbers that may have been harassed due to presence within the designated safety zone.

(4) Results of coordination with coastal marine mammal/sea turtle stranding networks."

The Gulf of Mexico permit required aerial surveys prior to the explosions to ensure that no marine mammals were within the safety radius. Post-explosion monitoring was required to search for the presence of dead or injured animals. The monitoring required for the Winston Churchill test added passive acoustic monitoring to the requirements.

During explosive platform removal in the North Sea, visual monitoring from the vessel, passive stereo hydrophones, and sonobuoys were used to detect marine mammals (Nedwell et al. 2002). A seal acoustic harassment device was used to scare resident seals away from the blasting site.

CHAPTER 8
DISCUSSION AND RECOMMENDATIONS

Previous chapters have reviewed the different technologies used for explosive structure removals, the physics of underwater detonations, and potential impacts on fishes, sea turtles, and marine mammals. This chapter discusses the findings, identifies data gaps, and recommends topics where further study would be appropriate.

This report has focused on three faunal groups: fishes, sea turtles, and marine mammals. Sea turtles and marine mammals are federally protected species for which death or injury of individual animals is a serious concern. In contrast, although many fish species associated with offshore platforms are federally managed, impacts on stocks or populations are the main concern, rather than death or injury of individuals. While mitigation and monitoring requirements have been established for marine mammals and turtles, there are no measures specifically developed to protect fishes; rather, it is assumed that fish kills are unavoidable during explosive structure removals.

Environmental data concerning platform removals serve two main purposes: 1) to allow impacts to be estimated (e.g., numbers of animals that may be killed or injured during structure removals); and 2) to aid in developing or refining mitigation measures that prevent or reduce the likelihood of impacts. Sources of data have included laboratory and field experiments, modeling studies, and anecdotal field observations. There are important differences among the three faunal groups discussed in this report with respect to the types and adequacy of data available (**Table 8.1**). In general, fishes are the best-studied group, and sea turtles the least studied.

Table 8.1

Types and Amounts of Data Available Regarding Impacts of Underwater Detonations on Fishes, Sea Turtles, and Marine Mammals

Group	Types of Data Available		
	Experimental Studies	Modeling	Anecdotal Observations
Fishes	• Numerous lab and field studies of explosive effects • Quantitative studies following actual structure removals	• Extensive	• Many observations (e.g., fish kills)
Sea turtles	• One study with caged turtles during platform removal (but no pressure measurements)	• Very limited	• Mortalities, injuries, strandings following detonations
Marine mammals	• Recent studies of explosive effects on dolphin carcasses • A few auditory effects studies but most not for explosives • Several studies on behavioral effects of seismic sources but limited relevance	• Limited efforts, mostly connected with ship shock trials; some models used data from terrestrial mammals	• Mortalities, injuries, strandings following detonations

8.1 Fishes

As discussed in **Section 6.1**, lethal effects of underwater explosions on numerous species of fishes have been studied in laboratory and field experiments and have been modeled extensively. These data and models have been used to calculate effect ranges. In addition, there have been studies specifically designed to estimate fish kills associated with structure removals in the Gulf of Mexico (Gitschlag et al. 2000).

One set of calculations reviewed in **Table 6.3** predicts effect ranges varying from 12 m for non-swimbladder species to 230 to 349 m for swimbladder species. Actual observations following structure removal detonations indicate most dead fishes were within 25 m, with numbers declining with distance out to 100 m (Gitschlag et al. 2000). Other surveys have shown that fish densities around platforms are highest within a horizontal distance of 18 to 50 m from the structure (Stanley and Wilson 1998, 2002). Therefore, it seems that most fishes associated with platforms are close enough to be killed or injured by a typical underwater detonation associated with structure removals. Of course, there are many variables affecting the fate of individual fishes, including their size, shape, vertical position in the water column, and orientation relative to the detonation source.

The main goal with respect to fish populations is predicting impacts rather than setting "safety ranges" for mitigation/monitoring. For predicting impacts, the empirical data from observations during actual structure removals (e.g., Gitschlag et al. 2000) would seem to be more useful than any attempt to calculate impacts based on experiments and models. Huge variations in the fish population itself, including numbers, species, sizes, and orientation and range from the detonation, would make it very difficult to accurately predict mortalities at any specific site. Since the data collected by Gitschlag et al. (2000) are limited in terms of depth range and geographic extent, additional studies may be needed to predict impacts in other areas, including deepwater environments.

8.2 Sea Turtles

As summarized in **Section 6.2**, there have been no laboratory studies of explosive impacts on sea turtles, and only limited field observations and experiments. In several instances, turtle injuries and mortalities (and in some cases, strandings) have been noted following underwater detonations. In one case where turtles were recovered after an open-water detonation, both charge weight and the approximate distances of the turtles from the detonation were known (O'Keeffe and Young 1984). Only one field experiment has been conducted in which sea turtles were exposed at known distances from a structure removal detonation; however, that study did not include concurrent pressure measurements to estimate the magnitude and duration of the shockwave received by the caged turtles (Klima et al. 1988). There have been several anecdotal reports of turtle deaths or strandings following structure removal detonations, including a few in the 15 years since the current mitigation/monitoring requirements were instituted (G.R. Gitschlag 2003, pers. comm., NOAA-F, Galveston, TX).

There have been no mechanistic models developed specifically to estimate impacts on sea turtles. Rather, it has been assumed that models developed for other vertebrates are reasonable approximations (Department of the Navy 2001). O'Keeffe and Young (1984) developed an equation for a turtle "safety range" based on field observations of three turtles following an open-water detonation. (The "safety range" is the distance beyond which turtles would not likely be killed or seriously injured.) The equation is simply based on cube-root scaling of the charge weight and the distance at which one turtle apparently was not affected. Young (1991) provided a more conservative version of the same equation but states that it is based on the criteria for platform removal established by the NMFS – i.e., it was not independently derived from observations or experimental data. The Department of the Navy (2001) also modeled effect ranges using the turtle death/injury observations from O'Keeffe and Young (1984) and a lung injury model developed by Goertner (1982) for small mammals. The results suggest that lung injury predictions for marine turtles are not inconsistent with predictions for small mammals.

An important goal with respect to sea turtles is calculating the areal extent of the mortality/injury zone so that this area can be monitored for turtles prior to detonations. In the 1988 "generic consultation" for structure removals in the Gulf of Mexico, the NMFS specified that the area within 3,000 ft (914 m) of the platform must be clear of visible sea turtles prior to detonation. The NMFS document does not specify the source of this number, but it apparently is based on the turtle death/injury observations to date (Klima et al. 1988) rather than any modeling. Klima et al. (1988) reported that of two turtles at this distance from platform removal detonations, one was normal and the other was rendered unconscious but appeared normal other than vasodilation around the throat and flippers.

Years of experience using the 3,000 ft (914 m) range monitored under the "generic consultation" suggests it has been effective in preventing most deaths or serious injuries of sea turtles (Gitschlag and Herczeg 1994; Gitschlag et al. 1997). In addition, the modeling analysis done by the Department of the Navy (2001), while not directly addressing the "safety range" for structure removals, suggests that the monitoring range specified in the "generic consultation" is likely to prevent death and lung injury to sea turtles. However, the empirical and theoretical basis for this specific number is weak. Although additional experiments with turtles and underwater explosives are unlikely, some knowledge gained from marine mammal studies in recent years may be applicable. It is recommended that existing data be reviewed and modeling conducted to calculate mortality/injury ranges for sea turtles using standard sound level metrics and incorporating detonation characteristics appropriate for offshore structure removals. This would provide a firmer foundation for a turtle "safety range."

8.3 Marine Mammals

As summarized in **Section 6.3**, only recently have experimental studies of explosive impacts on marine mammals been conducted, using animal carcasses (Myrick et al. 1990a; Ketten et al. 2003; Reidenberg and Laitman 2003). For many years, the only data available for predicting blast impacts on marine mammals were extrapolations from experiments on terrestrial mammals submerged in ponds (Richmond et al. 1973; Yelverton et al. 1973) and opportunistic post-mortem examinations of stranded animals following detonations (Ketten 1995).

There have been numerous attempts to model explosive impacts on marine mammals (Hill 1978; Goertner 1982; O'Keeffe and Young 1984; Young 1991; Ketten 1995; Department of the Navy 2001). Most of the research has focused on larger explosions associated with military testing such as ship shock trials. There also has been considerable research into sublethal auditory effects such as TTS and PTS (Ridgway et al. 1997; Finneran et al. 2000; Schlundt et al. 2000; Nachtigall et al. 2003), as well as behavioral responses to underwater noise. Much of the behavioral research has focused on seismic surveys using airguns rather than explosives (Richardson et al. 1995). Both blast injury and auditory effects are topics of ongoing investigations. Since existing marine mammal injury models are based on old and very limited data, it is likely that these models will be refined or new ones developed as more information becomes available.

For marine mammals as well as sea turtles, an important goal is calculating the likely extent of mortality and injury zones so that this area can be monitored for the presence of animals prior to detonations. Both the 1995 and 2002 regulations issued by the NMFS for incidental take of bottlenose and spotted dolphins in the Gulf of Mexico specified a "safety range" of 3,000 ft (914 m). This range for marine mammals is not based on any independent observations or modeling, but is simply the same range used for sea turtles under the "generic consultation" under Section 7 of the ESA (*Federal Register* 67 [148]:49,869-49,875).

Years of experience using the 3,000 ft (914 m) range monitored under the "generic consultation" suggests it has been effective in preventing most deaths or serious injuries of marine mammals (Gitschlag and Herczeg 1994; Gitschlag et al. 1997). However, as noted previously for sea turtles, the basis for this specific number is weak, and it was not even developed specifically for marine mammals. As additional data for blast injury in marine mammals become available and new or refined models are developed, it is recommended that mortality/injury zones be calculated for marine mammals using standard sound level metrics and incorporating detonation characteristics appropriate for offshore structure removals. This would provide a firmer foundation for a marine mammal "safety range."

Auditory effects such as TTS and PTS may occur beyond the "safety range" monitored during structure removals. These effects are of particular concern for marine mammals because of the regulatory implications of the MMPA, which prohibits "harassment." In various regulations for ship shock trial and seismic surveys, NOAA-F (previously NMFS) has accepted TTS as a criterion for marine mammal harassment. This is an area of ongoing research in which criteria are being developed and refined. The MMS should coordinate with NOAA-F to make use of the most recent findings and criteria in evaluating auditory impacts on marine mammals.

8.4 Physics of Underwater Detonations

As discussed in **Chapter 4**, the understanding of the physical principles of underwater detonations and of the propagation of shock and sonic waves in the surrounding medium is in itself quite well developed. There are, however, significant gaps in the application of this knowledge to actual removal of offshore structures. The containment effect provided by setting the structure-cutting charges below a minimum prescribed depth of sediment has not been documented for a comprehensive range of seafloor consistencies, with the result that the extent of the transmission of explosive energy into the water column may be significantly greater than expected (Nedwell et al. 2001). Much of what is known from experience regarding underwater detonations within the seafloor comes from rock demolition blasting, which by its very nature is performed in an altogether different medium from the relatively compliant upper layers of sediment in which structure-cutting charges are deployed.

A systematic research effort should be undertaken to model numerically the blast propagation for a range of charge sizes consistent with structure removal practices through a wide variety of sediment types and for different deployment depths below the sediment surface. Such modeling should extend to the transfer of energy into the water column both from the shock wave propagating through the interface and later decaying into an acoustic signal, and from the oscillating bubble of detonation gases when breakout into the water does take place. Experimental validation of model results at every possible opportunity should form an integral part of the study; this requires accurate measurement of acoustic levels, and preferably full waveform recording, at one or more locations in the water columns as well as characterization of the sediment firmness near the structures being removed, which could be done by penetrometer probing or similar techniques.

Once a reliable modeling approach has been generated and validated, forecasting of the acoustic levels distribution for planned operations would become possible from the type and location of the charge to be exploded, the depth of the water column, and the measured properties of the sediment in which the detonation occurs. In combination with improved estimation of impact thresholds based on appropriate and standardized sound metrics for marine mammals and turtles, such a modeling-based assessment of each planned decommissioning operation involving explosive removal of underwater structures would provide the best ability to minimize its repercussions on marine life.

CHAPTER 9
CONCLUSIONS

The most commonly used technique for explosive cutting of piles and conductors is with bulk explosive charges. Other techniques such as ring charges, focusing charges, linear shaped charges, and cutting tape are used in some instances. Increased use of techniques that involve smaller charge sizes could reduce potential impacts on marine life.

The physical principles of underwater detonations and of the propagation of shock and sonic waves in the surrounding medium are well understood, but there are significant gaps in applying this knowledge to actual removal of offshore structures. It is recommended that a research effort be undertaken to model numerically blast propagation for a range of charge sizes consistent with structure removal practices through a variety of sediment types and for different deployment depths below the sediment surface. Experimental validation of model results should form an integral part of the study. Ultimately, forecasting of the acoustic levels distribution for planned operations would become possible from the type and location of the charge to be exploded, the depth of the water column, and the measured properties of the sediment in which the detonation occurs.

Environmental data concerning platform removals serve two main purposes: 1) to allow impacts to be estimated (e.g., numbers of animals that may be killed or injured during structure removals); and 2) to aid in developing or refining mitigation measures that prevent or reduce the likelihood of impacts. Impact estimation is the main goal with respect to fishes, whereas for sea turtles and marine mammals, mitigation is the main goal (i.e., predicting the areal extent of mortality and injury zones so that these can be monitored prior to detonation to prevent impacts).

There are important differences among fishes, sea turtles, and marine mammals with respect to the types and adequacy of data available. In general, fishes are the best-studied group, and sea turtles the least studied. Effects of underwater explosions on fishes have been studied and modeled extensively, and field studies have quantified fish kills associated with structure removals in the Gulf of Mexico. For sea turtles, there have been no laboratory studies of blast injury, only limited field observations and experiments, and no mechanistic models developed specifically to estimate impacts. For many years, the main data available for predicting both blast and auditory impacts on marine mammals were extrapolations from terrestrial mammal studies, but ongoing studies are underway that will aid in developing improved mortality, injury, and auditory impact criteria.

For predicting impacts on fishes, the empirical data from observations during actual structure removals would seem to be more useful than any attempt to calculate impacts based on experiments or mechanistic models. Since existing observations

(Gitschlag et al. 2000) cover a limited geographic and water depth range, additional observations will be needed to better estimate future impacts.

Years of experience using the 3,000 ft (914 m) "safety range" monitored under the "generic consultation" suggest it has been effective in preventing most deaths and serious injuries of sea turtles and marine mammals. However, the empirical and theoretical basis for this specific number is weak. It is recommended that mortality/injury zones be calculated for sea turtles and marine mammals using standard sound level metrics and incorporating detonation characteristics appropriate for offshore structure removals. This would provide a firmer foundation for sea turtle and marine mammal "safety ranges."

In all three groups, there is relatively little information about sublethal impacts, particularly on the auditory system. While mitigation measures appear to be effective in preventing death or injury of mammals and turtles, it is uncertain to what extent sublethal effects may be occurring beyond the safety range. Recent and ongoing studies may provide the basis for estimating auditory impacts in marine mammals, which are particularly important in the regulatory context of "harassment" under the MMPA. There is almost no information to estimate auditory impacts on sea turtles.

The time interval between shots may be an important mitigation measure. The amount of time for an animal to recover from a shock wave is unknown. Do closely spaced shock waves, each of which is insufficient to cause damage, cause damage in proportion to the sum of the damage parameters or a sum of a time dependent percentage of damage parameters? The effect of short time intervals between blasts such as those used in Gulf of Mexico structure removals have not been addressed.

The ONR is conducting research on physical and auditory effects of blast parameters on marine mammals and detection of marine mammals with passive acoustic devices. Synergy between MMS and ONR in these areas of research would be fruitful. The Department of the Navy, Naval Surface Warfare Center is measuring actual blast parameters in the sea and working on new and/or revisions to blast propagation models. Synergy with this group would also be fruitful.

To date, mitigation and monitoring requirements for structure removals in the Gulf of Mexico have focused on sea turtles, bottlenose dolphins, and spotted dolphins. As structures are removed in greater water depths, many more species of marine mammals are likely to be encountered, including one endangered species (sperm whale) and other deep-diving species (such as beaked whales) that pose challenges for detection. Passive acoustic monitoring could aid in the detection of sperm whales. Not enough is known about the vocal behavior of beaked whales and some other species to determine the probability of their being detected by passive acoustic monitoring.

CHAPTER 10
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The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Minerals Revenue Management** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.