MARINE SEISMIC SURVEYS— A STUDY OF ENVIRONMENTAL IMPLICATIONS

R.D. McCauley[1], J. Fewtrell[2], A.J. Duncan[1], C. Jenner[3], M-N. Jenner[3], J.D. Penrose[1], R.I.T. Prince[4], A. Adhitya[5], J. Murdoch[6] and K. McCabe[3]
[1]Centre for Marine Science and Technology
Curtin University
GPO Box U1987
Perth WA 6845
[2]Aquatic Sciences
Curtin University
GPO Box U1987
Perth WA 6845
[3]Centre for Whale Research (WA)
PO Box 1622
Fremantle WA 6959
[4]Department of Conservation and Land Management
PO Box 51
Wanneroo WA 6946
[5]Physics Department
University of WA
Nedlands WA 6907
[6]NT Fisheries Department
Day Street
Darwin NT 0800
r.mccauley@cmst.curtin.edu.au

ABSTRACT

An experimental program was run by the Centre for Marine Science and Technology of Curtin University between March 1996 and October 1999 to study the environmental implications of offshore seismic survey noise. This work was initiated and sponsored by the Australian Petroleum Production and Exploration Association. The program:

- **characterised air gun signal measurements; modelled air gun array sources and horizontal air gun signal propagation;**
- **developed an 'exposure model' to predict the scale of potential biological effects for a given seismic survey over its duration;**
- **made observations of humpback whales traversing a 3D seismic survey;**
- **carried out experiments of approaching humpback whales with a single operating air gun;**
- **carried out trials with an air gun approaching a cage containing sea turtles, fishes or squid; and**
- **modelled the response of fish hearing systems to airgun signals.**

The generalised response of migrating humpback whales to a 3D seismic vessel was to take some avoidance manoeuvre at >4 km then to allow the seismic vessel to pass no closer than 3 km. Humpback pods containing cows which were involved in resting behaviour in key habitat types, as opposed to migrating animals, were more sensitive and showed an avoidance response estimated at 7–12 km from a large seismic source. Male humpbacks were attracted to a single operating air gun due to what was believed the similarity of an air gun signal and a whale breaching event (leaping clear of the water and slamming back in). Based on the response of captive animals to an approaching single air gun and scaling these results, indicated sea turtles displayed a general 'alarm' response at an estimated 2 km range from an operating seismic vessel and behaviour indicative of avoidance estimated at 1 km. Similar trials with captive fishes showed a generic fish 'alarm' response of swimming faster, swimming to the bottom, tightening school structure, or all three, at an estimated 2–5 km from a seismic source. Modelling the fish ear predicted that at ranges < 2 km from a seismic source the ear would begin a rapid increase in displacement parameters. Captive fish exposed to short range air gun signals were seen to have some damaged hearing structures, but showed no evidence of increased stress. Captive squid showed a strong startle response to nearby air gun start up and evidence that they would significantly alter their behaviour at an estimated 2–5 km from an approaching large seismic source.

KEYWORDS

Seismic, noise effects, fish, whales, squid, sea turtles, underwater sound, air guns.

INTRODUCTION

Offshore seismic surveys involve the use of high energy noise sources operated in the water column to probe below the seafloor. Almost all routinely used seismic sources involve the rapid release of compressed air to produce an impulsive signal. These signals are directed downwards through the seabed, to be reflected upwards again by density or velocity discontinuities within the underlying rock strata. The returned signals are received, stored and processed by geophysicists to give profiles of the seafloor, commonly to depths of 10 km. The technique, essential for oil and gas exploration and development, is now commonly used to monitor the flow of hydrocarbons from producing fields and in modified forms is widely used in maritime engineering surveys.

The high source levels involved in seismic surveys has raised concern over their environmental effects and possible effects on commercial fishing operations. In response to this concern, the Australian Petroleum Production and Exploration Association (APPEA) in conjunction with the Energy Research and Development Corporation (ERDC) pro-actively funded a three year multi-disciplinary project based at Curtin University to study the environmental implications of offshore seismic techniques in the Australian context. This project ran over March 1996 to October 1999. A discussion of these results is presented here.

The project described here has set out to link the physical aspects involved in the transmission of air gun signals through the sea to studies on the response of a range of marine species to nearby air gun signals. Thus it has been a multi-disciplinary approach. The project has:

- characterised the measurement of air gun signals;
- modelled air gun array configurations for source level with aspect and elevation;
- carried out horizontal propagation modelling of air gun signals;
- described sets of field measurements of a 3D array and single air gun;
- developed a model to predict exposure through time for a given survey configuration, and by linking this to effect types, predict regions impacted by a given survey;
- monitored the movement and behaviour of humpback whales through an area in which a 3D seismic survey was running;
- carried out 16 trials where humpback whales were approached with a single operating air gun to gauge responses;
- carried out two trials where captive green and loggerhead turtles were approached with a single operating air gun;
- carried out trials of exposing various fishes to air gun noise and measured behavioural, physiological and pathological effects;
- modelled the response of fish otoliths to applied air gun signals; and
- carried out trials of exposing squid to air gun approaches to gauge behavioural responses.

The following discussion briefly summarises the findings listed above, and is as presented in the final report for this program. Readers are referred to the full report (McCauley et al, 2000) for methods, results and appropriate permitting details. This report is available from the APPEA website at http://www.appea.com.au.

DISCUSSION

Physical factors

AIR GUN SIGNAL CHARACTERISATION

Extensive sets of measurements made at ranges of 5–6,000 m from a single 20 cui air gun used in experimental trials and of a 2,678 cui 3D air gun array from 1.5-64 km range revealed that the most consistent measure of the received air gun signal was some measure of its energy. This is as suggested in Richardson et al (1995) for pulsed sounds. Typically an air gun signals' rms (or mean square pressure) or peak pressure have been reported in the literature. It was found that under certain circumstance measurements which used time integration over the received air gun pulse (i.e. rms) suffered due to factors complicating a repeatable measure of the signals start and end time, or pulse duration. Inconsistencies in the pulse length definition then biassed the time integrated measure. Factors which tended to alter the measured pulse length were: the air gun bubble pulse; headwaves for seafloor coupled hydrophones in an appropriate seabed type; or for distant air gun signals, high background noise or biological transients such as fish and whale calling. Although air gun arrays are designed to suppress bubble pulse signals in the downward direction they may not do this in the lateral or horizontal direction, which is of importance for biological effects studies. Headwaves are sound waves channelled along the seabed water interface. The presence of the bubble pulse or headwaves in the received signal often acts to increase the calculated signal time without contributing significantly to the total energy content of the signal. This dragged the time integrated measure down.

In the present work a standardised method based on the digitised signal was used for generating a set of parameters describing a received air gun signal. Of these parameters the 'equivalent energy' in units of dB re 1 $\mu Pa^2.s$ was found the best signal descriptor and was used throughout all analysis in this project. Note that this measure is not an energy unit, but since it is proportional to energy it has been termed 'equivalent energy' throughout this document. For the different sources measured, empirically derived corrections were used to convert these equivalent energy units to rms or peak pressure values for comparison with other workers. Converting the 'equivalent energy' units to rms values is valid since the rms pressure (in dB re 1 μPa) is equal to the 'equivalent energy' measure minus $10*\log_{10}$(air gun pulse duration, in seconds). From the measurements made in this report the rms pressure in dB re 1 μPa was equal to the 'equivalent energy' plus 11.4 to 14.6 dB, depending on the source and local environment over which the measurements were taken. Note that the correction is positive since the air gun signal duration was always less than one second.

Converting either rms or 'equivalent energy' measures to peak–peak pressure units is not technically valid, but since many workers have used peak pressure units (or some derivation of), to describe sound levels in their results, there has been no option but to do this. Empirically derived correction factors from many thousands of air gun measurements made in this report, were found to be consistent over ranges out to many kilometres. The peak-peak pressure levels from a received air gun signal were 27.3 to 30.5 dB above the equivalent energy units. Again this varied depending on the source and local environment in which the measurements were made.

For ease of comparison with other literature this discussion preferentially presents the air gun levels as rms units. For the results arising from this report these units are either as measured directly from air gun signal data sets or derived from equivalent energy measurements, for the appropriate source type and local environment.

Measured and modelled air gun signals

The sets of air gun signals measured elaborated many of the complications inherent in describing the received level of a signal at range from an air gun source in shallow water. These complications included:

- directionality inherent in an air gun array;
- receiver depth;
- the seabed properties;
- the array operating state;
- the source depth;
- water depth along the propagation path; and
- sound velocity profile in the water and seabed

A 2D and 3D array were each modelled for source directionality. Each showed an increase in higher frequency energy off the array beam while the 2D array also had highest levels of low frequency energy radiated fore and aft relative to the array tow axis. Measurements of the 3D array showed that the abeam directionality was enhanced at range, such that the signal level could increase by up to almost 10 dB at a given range as the receiver came abeam. This effect was greatest higher in the water column.

Measurements and modelling showed that at a specified range there were differences in the vertical sound intensity profile. A consistent trend for lower received levels on moving towards the surface was observed. For example the 3D array measured at 1.6–1.8 km range showed a 6 dB decrease in level on moving from 40–5 m depth. Modelling a single air gun in 20 m water depth showed that at range from the source the maximum level extended from approximately midwater to the bottom, and that levels near the water surface could be 10 dB lower.

Seabed properties are known to be crucial in horizontal sound propagation. Sound energy from an in-water noise source may reflect directly off the bottom or may enter the bottom and subsequently be reflected or refracted back into the water. Because of its military implications a large literature base exists on sound propagation in shallow water (e.g. reviews in: Jensen et al, 1994; or Medwin and Clay, 1998). Depending on the bottom type, the frequencies of interest and the water depth, it may be that a precise definition of the physical seabed parameters to at least 50–100 m below the seafloor is required to accurately define the horizontal propagation along any travel path. In Australian waters this level of detail is generally not available.

The importance of seabed parameters was emphasised during humpback whale trials in Exmouth Gulf, Western Australia. During 16 trials where humpback whales were approached with a single operating air gun (Bolt 600B, 20 cui chamber, 10 MPa operating pressure) to gauge responses, nine sets of measurements were made of the air gun from 0.17–6.8 km off. All measurements were made within an approximate 20 x 30 km area, in water depths of 16–20 m. It was anticipated that from these empirical measurements a single fitted curve could be derived to describe the air gun level received by the whale. This was not the case, rather two general sets of signal loss with range curves were measured, ‘good’ and ‘bad’ propagation conditions with differences in broadband air gun level of up to 10 dB at one km range. The ‘good’ propagation curves returned far more higher frequency energy (160-1,000 Hz) than the set of ‘bad’ propagation curves. Investigation of the available literature suggested that patchily distributed cemented limestone pavements were common throughout the region. Thus sound propagation models were run using estimates of the seabed type with and without a cemented pavement. These grossly matched the frequency content observed and the received air gun level curves, suggesting that the two sets of curves observed were probably due to the presence or absence of a shallow cemented layer. The large differences in level observed for the same source at a given range within the bay and its patchy distribution in a relatively small space highlighted the localised importance of the seabed type in determining sound propagation.

During 3D seismic operations two air gun arrays are towed parallel to each other and equally spaced about the tow direction. These are fired in a flip-flop fashion, alternating between port and starboard arrays. The arrays are normally identical in nature, towed at the same depth and operated at the same pressure. Measurements of port and starboard 2,678 cui 3D array’s revealed that although when averaged over many signals there was no net difference in received level at range between port and starboard, consecutive air gun signals were consistently different, with up to a 9 dB variation. It was believed slight differences in the orientations of receivers to each array, alignments and depths of array components and of functioning air guns within each array contributed to the measured differences. Again this exemplified the difficulty of predicting the received air gun level for a specified air gun array and the requirement for a detailed study of the source and environent.

Modelling was carried out to determine the effect of air gun source depth on horizontal sound propagation. Source depth plays a crucial role in determining an air gun array downward performance, since it dictates the time delay for the surface reflected signal which in turn affects the frequency content of the downward directed signal of primary interest to the geophysicist. Modelling a single air gun in Exmouth Gulf for horizontal sound propagation found that increasing source depth consistently increased the received signal at any specified horizontal range and receiver depth. This was a function of the modal structure inherent in shallow water, such that the optimal position for placement of the source was at the apex of the primary mode at each frequency. For the predominant frequencies in the example used this mode occurred near midwater (at 10 m depth in 20 m water). In the model run used, increasing the source depth from 2.5 to 6 m resulted in a mean 8 dB signal increase for a receiver at 10 m depth over ranges of 0.15-5 km.

Differences in travel path bathymetry profiles also played an important role in determining received levels. Many sets of measurements were made of the 2,678 cui 3D array from a receiver set on the bottom in 32 m of water from the array source in 100–120 m of water. These travel paths then involved up-slope propagation. Because of the increasing number of bottom-surface bounces and increasingly steeper angles involved (closer to the vertical axis) as the water shallowed, this type of propagation results in much larger signal attenuations compared to measurement sets over similar ranges but constant water depths. In one instance the signal was not audible at a receiver in 10 m of water 28 km from the source in 130 m of water. Measurements at similar ranges in deeper water returned clearly audible signals.

A model was built to predict source levels of any given air gun array configuration for a specified azimuth (horizontal aspect), elevation (vertical aspect) and the presence or absence of the source ghost. Such models are routinely used by geophysical contractors to develop particular air gun array configurations, but these are proprietary in nature with their details not available. The source model produced was based on a modified version of an air gun bubble model presented by Johnson (1994) and required some source specifications from the geophysical contractor to 'tune' the output.

There are a number of numerical models available for the calculation of horizontal acoustic propagation. These include ray tracing, normal mode and parabolic equation models. Each has its own strengths and weaknesses. Some are best suited to shallow water, others to deep water, some can deal with complex bathymetry profiles, others require a fixed water depth, some return vertical sound intensity profiles through the water column, others output for a fixed depth only, some can deal with shear waves, others cannot. The choice of horizontal propagation model thus depends on the circumstances dictated by the environment in question. All of these models run at a single frequency only. Thus to characterise a source with complex frequency components, such as an air gun array, the chosen model needs to be run at many frequencies and the resultant energy summed to give the broadband received signal level.

Given all of the above factors and others not discussed such as sound speed profiles within the water column, it is believed that at present, predicting the horizontal sound propagation from any specified air gun array source needs to be done on a case by case basis. There are some generalisations which can be made such as those listed above, but accurately predicting levels at specified ranges and water depths requires modelling of the source and local environment. It would be hoped that over time enough air gun signal measurement and modelling sets would become available from different Australian environments, so that historical data sets could be used to predict received air gun level with range. At present only the measurements described above, for two exploration regions, are available.

Air gun exposure modelling

Although it is a valuable exercise to model the horizontal propagation of single air gun shots this tells us little of the exposures received through time for a constantly moving seismic source. Seismic vessels steam at around 3–5 knots (1.5–2.5 ms^{-1}) along straight tracklines in the region of the survey for weeks to months operating at an 8–15 s repetition rate. The repetition rate is determined by the hydrophone spacing in the streamers, such that optimally an air gun pulse is fired at this spacing. A 3D seismic survey may concentrate activity in a few hundred km^2 for upwards of a month, with a trackline coverage every 100 m.

The results of studies into the response of marine animals here and elsewhere suggest that above threshold level air gun signals, behavioural changes occur in many species and that with increasing air gun level these behavioural changes become increasingly significant. Assuming one can predict the threshold level at which the behaviour of a particular group of marine animals will be altered in some fashion, suggested presenting the seismic survey exposure history as the proportion of a region experiencing levels above a specified threshold over the seismic survey duration.

Thus an exposure model was developed which for any given seismic survey source, trackline configuration and set of environmental parameters, returned an estimate of exposure through time as the number of air gun signals exceeding a specified threshold, on a spatial grid. This exercise was carried out for an example seismic survey. The model produced a contour plot of the number of received air gun shots at a specified receiver depth which exceeded the threshold level for the full seismic survey duration (121 days in the example used). This contour plot could be interpreted as a probability plot, showing a scale of potential disturbance for the entire seismic region over the survey duration. The model saved the data for each period of consecutive operations (i.e. each period with no breaks in operations for turns, dropouts, gear failures etc). Thus the data could be further processed and presented on a different time scale, perhaps as the number of shots exceeding the threshold, per-hour, per-day.

It was intended that this exposure model could be used to gauge the potential ecological scale of biological effects. The particular exercise carried out was done post-survey, but could just as easily be done prior to any seismic survey, and thus would give some prediction of the potential scale of any effects. It is believed this type of modelling would be a useful tool for evaluating potential conflicts. With refinements and considerable computer processing power, the technique could also be used to optimise seismic survey trackline configurations so as to minimise possible environmental implications.

Humpback Whale response to air guns

Observations were made of southward migrating humpback whales transiting the region of a 3D seismic survey. The whales were migrating south west, while the seismic vessel ran east west tracklines straddling the migratory route. Complementary to this work 16 approach trials were carried out where humpback whales were observed for around an hour, approached with a single operating air gun then followed for another hour. Movement patterns and behaviours were logged for any changes correlating with the air gun approach. Preliminary results of this work are presented in McCauley et al, 1998.

HUMPBACK MOVEMENTS ABOUT AN OPERATING SEISMIC VESSEL

The study region for the seismic survey vessel operations was north east of North West Cape, off Exmouth. Humpback whales transitting the seismic region appeared to move south from the Monte Bello Islands towards North West Cape in blue offshore water in a broad band that extended at least as far offshore as the sampling effort undertaken. This was out to 240 m of water 38 km from the 20 m depth contour. Animals seen in this region were migrating, which involved continuous swimming on a southwesterly course or southwesterly swimming interrupted by short to long resting periods. A considerable number of whales tended to cross into the shallow water inside the island chain extending north east of North West Cape between Bessieres Island and the Murion Islands. Few animals were seen in shallow water to the east of Bessieres Island, while many were seen to the west of it. After passing from the offshore region into shallow water these animals were believed to then swim into Exmouth Gulf. Animals seen inside Exmouth Gulf showed much more random swimming patterns than migrating animals seen in the blue water, and were either resting or engaged in courting behaviours. This behavioural distinction was important in assessing results. It also should be pointed out that adult humpback whales do not feed when in tropical Australian waters during their migration. The significant feeding that does occur is of cows feeding calves.

In the region of the seismic survey, the distributions of whale pods sighted during aerial surveys undertaken before the seismic survey began, during the seismic survey, and of pods sighted from the seismic survey vessel appeared to be uniformly distributed across the depth contours. There was no obvious evidence that whales were displaced inshore or offshore by the seismic survey.

Using data from all whale observations made from the seismic survey vessel, there was no discernible differences in the number of whales sighted per observation block (40 minute period) between observation blocks with the guns-on or guns-off for the entire block. When broken down by range category, the guns-off sighting rates were considerably higher from ranges near the vessel to 3 km than the guns-on sightings in the same range category.

This observation suggests localised avoidance of the operating air gun vessel during periods with the air guns on and agrees with published findings. These indicate that at some range most whales will avoid an operating seismic vessel. Richardson et al (1995) summarises the findings of many researchers whom have found that gray and bowhead whales generally avoid seismic vessels where the received sound level is between 150–180 dB re 1 µPa rms. The level at 3 km from the seismic vessel from which the humpback observations were made was in the range 157–164 dB re 1 µPa rms for a receiver at 32 m depth, which is in agreement with the standoff level given for gray and bowhead whales.

At >3 km from the operating seismic vessel the guns-on sighting rates were considerably higher than the guns-off observations in similar range categories. The higher sighting rates observed at ranges >3 km during guns-on observations suggested that at these ranges some bias existed in the availability of animals for sighting during guns-on periods or that whales were attracted to the operating air gun vessel.

A possible sighting bias was the tendency for whales to utilise the sound shadow near the sea surface to reduce the received sound loading. Four follows were made of humpback whales moving about the operating seismic vessel. Two of the ‘follows’ involved whales which spent an inordinate amount of time at the surface. In follow 1 a single animal swam entirely at the surface to cross 1.5 km off the bows of the operating seismic vessel. In follow 2 a cow and calf remained lying at the surface while the operating seismic vessel passed 3 km north of them. It is well known that as one approaches the sea surface the noise level of a nearby sound source will decrease substantially due to phase cancellation of the direct and surface reflected signals. This effect is exemplified for shallow sound sources (the air gun arrays were towed at 7 m depth). It is plausible that these whales were using this effect to reduce the air gun sound loading received and thus increased their sighting availability.

It was found during experimental exposures that what were believed to be male humpbacks were attracted to a single operating air gun possibly due to its similarity to the sound produced by humpback whales breaching (discussed below). Thus there may have been several reasons for the increased sighting rate at ranges > 3 km when the seismic vessel was operating its air gun arrays.

The pod sighting rates observed during blocks when the air guns were switched on/off or off/on were higher than the sighting rates during guns-continually-on or guns-continually-off observation blocks for the range categories from 0.75–3 km. These higher rates could be explained by:

1. a startle response bringing animals to the surface for air guns turned on after being off for a protracted period; or
2. an investigative response where whales tend to come

to the surface for air guns turned off after being on for a protracted period.

Startle responses to seismic survey sounds have been reported for humpbacks at levels of 150-169 dB re 1 µPa (effective pulse pressure, believed equivalent to rms measure) by Malme et al (1985).

The first 'follow' made of whales moving nearby to the operating seismic vessel showed that on occasions whales would deliberately pass an operating seismic vessel at comparatively short range (1.5 km), albeit with a somewhat radical manoeuvre. Two follows involved pods on interception courses with the seismic vessel. These pods consistently made course and speed changes at 4-5 km to avoid the operating seismic vessel, standing off at 3-4 km at an estimated received level of 157-164 dB re 1 µPa rms. The most consistent manoeuvre seen by intercepting whale pods from the four follows and from the seismic vessel was for the pod to alter course and speed so as to pass behind the operating vessel. During follow 2 a cow calf pair were seen to react by swimming strongly to the air gun array starting up on an almost direct interception course at 11 km and a received level of 139 dB re 1 µPa rms. But this pod only swam to a position 3 km south of the approaching vessels' trackline then stayed there resting quietly at the surface while the vessel passed to the north and departed. Based on blow rates the animals did not seem to be under any duress.

HUMPBACK APPROACH TRIALS

The 16 approach trials carried out in Exmouth Gulf revealed that humpback pods which contained females consistently avoided an approaching single operating air gun (Bolt 600B, 20 cui chamber) at a mean range of 1.3 km. Avoidance manoeuvres were evident before standoff at ranges from 1.22–4.4 km. In one instance a startle response was observed. The mean air gun level for avoidance was 140 dB re 1 µPa rms, the mean standoff range at 143 dB re 1 µPa rms and the startle response observed at 112 dB re 1 µPa rms. These levels are considerably less than those observed from the operating seismic vessel observations made outside Exmouth Gulf and from those published for gray and bowhead whales. More recent work on migrating bowhead whales has shown air gun levels for avoidance less than those observed for the resting humpback whales (W.J. Richardson, LGL. Ltd. Canada, pers. comm.). For the observations made of humpbacks here, it is believed the differences in behavioural state of the animals at the times of the respective exposures primarily accounted for the difference in response levels. Pods containing females and inside Exmouth Gulf were invariably resting or attempting to rest. Resting was a particularly important behavioural state for cow-calf pods. It is believed that whales engaged in such behaviours were more sensitive to the approaching air gun than animals involved in the purposeful migratory swimming behaviour seen as the animals passed through the region of the seismic survey to the north east of North West Cape.

Although pods containing females kept the air gun at some standoff range during the Exmouth Gulf trials, in nine of the 16 trials mostly single, large, mature humpbacks approached the operating air gun to 100–400 m, investigated it, then swam off. These approaches were deliberate, direct and often at speed with one incoming whale clocked at 8 kn. These whales would have received maximum air gun signals at 100 m of 179 dB re 1 µPa rms (or 195 dB re 1 µPa peak–peak). This level is equivalent to the highest peak-peak source level (level at one metre) of song components measured in the 1994 humpback whale song in Hervey Bay by McCauley et al (1996), or as given by Thompson et al (1986) for humpback whale sounds in Alaska, of 192 dB re 1µPa peak-peak at one metre.

Fortuitously breaching signals produced by a large cow leaping clear or partly clear of the water and slamming back in were measured after one of the sets of approach trials. These breaching signals were measured over 0.1–1 km range. The underwater signals produced by this animal breaching were audibly similar to air gun signals. The author has noted this before from recording sets in Hervey Bay, Queensland ('rifle' shots, McCauley et al, 1996) and from sets with continual humpback singing with breaching from the Kimberley region of Western Australia (personal observation). On analysis of the breaching signals it was found that they could be matched well with air gun signals based on waveform, energy content and frequency spectra. As an example a breaching signal as recorded at 100-200 m matched a signal from a 3D seismic array as recorded at 6.8 km range and a 20 m depth hydrophone, based on equivalent energy levels.

We speculate that given the similarities between air gun and breaching signals male humpback whales may identify air gun signals as a 'competitor'. The songs mostly male humpback whales generate are possibly used to attract females and/or to signal other males as to their presence and breeding intentions. Sustained air gun signals may present as an acoustic 'threat' to the integrity of a singer or as an event worth investigating. Thus we believe that the animals which investigated the single air gun during the Exmouth Gulf approach trials were males, intent on investigating a potential 'competitor', or what they perceived as a breaching event. We stress that this is speculative.

MANAGEMENT IMPLICATIONS FOR LARGE BALEEN WHALES

Cow/calf pairs are in the author's experience more likely to exhibit an avoidance response to man-made sounds they are unaccustomed to. Thus any management issues relating to seismic surveys should consider the cow/calf responses as the defining limits. Adult male humpback whales intent on mating often doggedly pursue available females. Swimming towards or around an operating seismic vessel may be a small obstacle to a male humpback whale who has sensed a sexually available female on the other side. This was borne out by the observation of a male animal swimming across the bows of the operating seismic vessel.

For management purposes the distinction is made between migratory or transiting whales versus whales which remain in a general area for socialising, resting, calving, mating, feeding or some other purpose ('key habitat' type). Migratory whales are those involved in travelling, for Australian humpbacks this is very purposeful for northerly travelling whales and more meandering for southerly travelling whales.

For the humpback whale pods migrating south outside the 20 m depth contour the major implication of the seismic survey vessel operating across their migration track seems to have been localised displacement about the seismic vessel. Animals on interception courses essentially maintained their course until at 4–5 km, whence they adjusted course and speed to pass by the operating vessel, allowing an avoidance range of around 3 km. Some animals approached the vessel closer, with on one occasion a single animal seen to deliberately cross the vessels bow while swimming at high speed and on two occasions the vessel stopping work when single animals were sighted within 1–2 km. There was no evidence of any gross changes in the southerly migration track in the region of the seismic survey, such as displacement inshore or offshore during times when the vessel was operating.

Given that only localised avoidance was seen by migrating whales one would conclude that any 'risk factor' associated with the seismic survey was confined to a comparatively short period and small range displacement.

The peak-peak levels of the 3D seismic array measured were of the order of 182 dB re 1 µPa at 1.6 km, which was below the source level of the highest components of humpback whale song or breaching/pec slapping sounds (e.g. 192 dB re 1 µPa peak, Thompson et al 1986 for pec slapping, 192 dB re 1 mPa peak–peak McCauley et al 1996 for some song components). The breaching signal measured at 100–200 m range gave a received peak-peak level of 160 dB re 1 µPa. Using spherical spreading and a 150 m range gives a crude source level for this signal of 182 dB re 1 mPa peak-peak at one metre. Thus at 1.6 km the received 3D air gun signal was within the range which humpback whales would be expected to cope with physiologically, since it would be difficult to argue that humpback whale song or natural breaching events can cause physiological problems to the animals. McCauley et al (1996) report on a humpback whale singing persistently within 20–50 m of other whales and during the observation in Exmouth of the cow breaching the calf was always within 20–50 m of the landing cow. This natural exposure to intense signals coupled with the fact that humpbacks were seen to be actively utilising the 'sound shadow' near the surface when in the vicinity of seismic operations, implies it is probable that humpbacks are not at physiological risk unless at short range from a large air gun array.

Using an algorithm generated to estimate the received level of a 3D array at 32 m depth which accounted for beam patterns, the range at which the air gun array peak-peak signal matched the known source level of humpback sounds was calculated at 0.95–1.4 km for a receiver at 32 m depth. This assumed a 30 dB correction to shift the air gun units from equivalent energy to peak-peak pressure, and a maximum humpback song component source level of 192 dB re 1 µPa peak–peak. The generated curve with angle from the air gun array bow is shown on Figure 1.

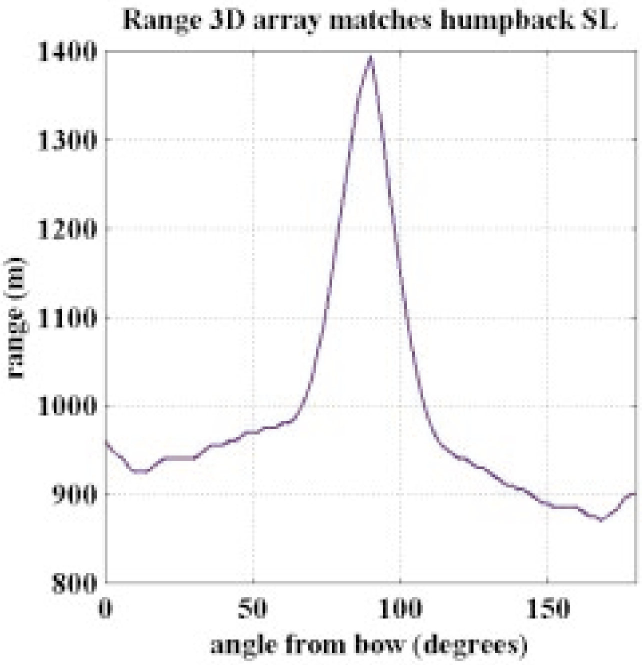

Figure 1. Calculated range at which the received air-gun level from a 2,678 cui 3D array at 32 m depth matched the highest recorded level of humpback song.

Given these two factors, that displacements to migratory animals were comparatively short in time and involved small range changes and the low chance of physiological effects, then there appears to be a low risk for migratory animals exposed to seismic activity.

The same could not be said for humpback whales which are not migrating, but which are relatively sedentary in an area and involved in some behavioural activity which is important from a population perspective (key habitats). For humpback whales along the Western Australian coast such areas include at least: the southern Kimberleys between Broome and the northern end of Camden Sound; Exmouth Gulf; Shark Bay; waters to the north and northeast of Rottnest Island; and Geographe Bay, during the late winter-spring months. In particular C and M-N Jenner have identified the southern Kimberley region as a calving ground used by a large portion of the Western Australian humpback whale population.

In these key habitat areas the possibly lower threshold for response to air gun signals could be expected to result in displacement by an operating seismic survey vessel at ranges greater than observed for animals outside these habitat types. Scaling the air gun level results of the approach trials using the single air gun, where avoidance occurred at 1.3 km in a key habitat, to levels about the 3D array measurements described, gave a potential range of avoidance about an operating seismic vessel of 7–12 km. This 7–12 km range would only apply to whales in a key habitat type, and then may be lower given different sound propagation conditions.

Displacement by a continually operating seismic vessel in a key habitat type could have much more profound and serious effects on individual animals and the population than exposure for animals migrating or not in a key habitat type. For example Exmouth Gulf is used as a resting area by southerly travelling humpback whales, specifically by cows resting and feeding 4–8-week-old calves. At this stage of their lives the calves are small, comparatively weak and possibly vulnerable to predation and exhaustion. The potential continual dislocation of these animals in a confined area would interrupt this resting and feeding stage, with potentially more serious consequences than any localised avoidance response to an operating seismic vessel as seen during their migratory swimming behaviour. Similarly any repetitive displacement or disruption of animals on their calving grounds during the time when they are present (e.g. southern Kimberleys for Western Australian humpbacks during July to late September), may have serious consequences at the population level.

Sea turtle response to air guns

Two trials were conducted with caged sea turtles and an approaching-departing single air gun (Bolt 600B, 20 cui chamber) to gauge behavioural responses. The trials were conducted on a green (*Chelonia mydas*) and loggerhead (*Caretta caretta*) turtle and separated by two days. The first trial involved 2:04 hrs of air gun exposure and the second 1:01 hr. Each trial used a 10 s repetition rate.

The trials were consistent and showed that above an air gun level of 166 dB re 1 µPa rms the turtles noticeably increased their swimming activity compared to non air gun operation periods and above 175 dB re 1 µPa rms their behaviour became more erratic possibly indicating the turtles were in an agitated state. The increase in swimming behaviour tracked the received air gun level, in that the turtles spent increasingly more time swimming as the air gun level increased. The point at which the turtles showed the more erratic behaviour would be expected to approximately equal the point at which avoidance would occur for unrestrained turtles.

Two similar trials have been reported in the literature. O'Hara (1990) reported that loggerhead turtles kept in a 300 x 45 m enclosure in a 10 m deep canal maintained a standoff range of 30 m from a Bolt 600B air gun with 10 cui chamber and two Bolt 'poppers', all operating at 2,000 psi (14 MPa), suspended at 2 m depth and operated at a 15 s interval. O'Hara did not measure the received air gun levels. The paper does indicate that the Bolt air gun produced most of the energy in the received signal. In experiments conducted in this report an identical Bolt 600B air gun with a 20 cui chamber deployed at 5 m depth in 10 m of water using a 1,500 psi (10 MPa) operating pressure produced a signal of 176 dB re 1 µPa rms at 30 m range and 3 m depth receiver. We found that for every MPa increase in the air gun operating pressure an approximate 1 dB increase in signal level was achieved. Thus assuming in O'Hara's experiment that the significant signal energy received was produced primarily by the Bolt air gun only, that the increased level expected from the larger chamber size in our trials was compensated by the lower operating pressure (3–4 dB difference), and similar sound propagation for the similar water depths (a reasonable assumption at such short range), then we could expect that the level at which O'Hara saw avoidance was around 175–176 dB re 1 µPa rms. This agrees with the value observed in our trials at which the turtle behaviour became more erratic and reinforces the view that at this level active avoidance of the air gun source would occur.

Moein et al (1994) using loggerhead turtles enclosed in an 18 m x 61 m x 3.6 m enclosure in a river, measured avoidance behaviour, physiological response and electroencephalogram measurements of hearing capability, in response to an operating air gun. The air gun (s) were deployed and operated from the net ends at 5–6 s intervals for five minute periods. They quote three air gun levels received by the turtles, 175, 177 and 179 dB, but do not give the units nor the ranges from the source at which these refer to. Details of the air gun, its operational pressure, deployment depth and sound levels experienced by the turtles throughout the cage were not given. Considering the results from all turtles tested (11 individuals six trials each) avoidance was seen during the first presentation of the air gun exposure at a mean range of 24 m. Further trials several days afterwards did not elicit statistically significant avoidance. The physiological measures did show evidence of increased stress, but the effects of handling turtles for sampling were not accounted for thus the stress increase could not be attributed to the air gun operations. A temporary reduction in hearing capability was evident from the neurophysiological measurements but this effect was temporary and the turtles hearing returned to pre-test levels at the end of two weeks.

The avoidance behaviour described by Moein et al (1994) is in partial agreement with the findings here. The evidence from the caged experiments here and from that of O'Hara was that at some level the turtles would show avoidance of the operating air gun. The behavioural results in our caged trials were consistent between trials two days apart using the same turtles. The results of Moein et al (1994) showed that the avoidance behaviour was not statistically significant for loggerheads receiving repeated air gun exposures several days after their first exposure. They concluded that this was due to either habituation or a temporary shift in the turtles hearing capability.

There were differences in the presentation of the air gun signals between these experiments. In the trials reported here the air gun signal was ramped up by the air gun approach-departure scenario used. This meant the turtles only received a small number of moderate to very high level air gun signals. This type of exposure is similar to that which would be experienced by an approaching and departing seismic survey vessel. In contrast the experiments of Moein et al used a fixed air gun source operated at constant range. Although the source details of the Moein et al trials were not stated, to give some idea of the levels experienced, a Bolt 600B air gun with 20 cui chamber, 5 m gun depth, 10 MPa operating pressure for a receiver 3 m deep in 10 m water depth, produces a received level of 176 and 172–175 dB re 1 μPa rms at 24 and 64 m respectively (24 m being the mean avoidance range for first exposure given by Moein et al, 64 m being their maximum cage length). Comparing this with the received air gun shot levels for the first sea turtle trial reported here, then a full trial of the Moein et al experiments exposed the turtles to ~180 shots > 172 dB re 1 μPa rms (assuming three five minute periods with 5 s operation rate and level at 64 m of 172 dB re 1 μPa rms), whereas the first sea turtle trial here exposed the turtles to only 97 shots > 172 dB re 1 μPa rms. Thus the temporary shift in hearing thresholds observed by Moein et al, which may have played a part in the lack of avoidance seen in trials repeated several days after a turtle's first air gun exposure, may have been less important in the trials carried out here, possibly because of the different air gun regimes used between trials.

Lenhardt (1994) reported on a swimming response from loggerhead turtles in large shallow tanks on presentation of low frequency (< 100 Hz) tones. Although the results are not directly applicable to impulsive air gun signals they suggest that the increase in swimming behaviour seen in our trials and by Lenhardt (1994) may be a generic sea turtle 'alarm' response.

Implications of seismic operations for sea-turtles

The available evidence from these trials and the literature suggests that sea-turtles may begin to show behavioural responses to an approaching air gun array at a received level around 166 dB re 1 μPa rms and avoidance around 175 dB re 1 μPa rms. From measurements of a seismic vessel operating 3D air gun arrays in 100–120 m water depth this corresponds to behavioural changes at around 2 km and avoidance around 1 km. Important sea turtle habitats mostly occur in shallower water, often less than 20 m deep. The propagation of an air gun array in such water depths may be vastly different than that for the array measured in 120 m water depth. One would generally expect that sound propagation in water < 20 m deep would be significantly worse, that is the signal would not carry as far. But under some circumstances dictated by the seabed properties, this may not be so. Thus, these one and two km response and avoidance ranges are a guide only and may be more or less, depending on the source and specific environmental conditions.

A wild card for sea turtle response to air gun signals is the sediment borne headwave signals. These may be significant in some seabed types such as seen within Exmouth Gulf. For bottom coupled hydrophones in some areas within Exmouth Gulf an air gun signals headwave energy exceeded the waterborne energy at a sufficient range. Conversely some seabed types will not support headwaves at all. Sea turtles are believed to have some capability of bone conducted hearing (Lenhardt et al 1983) and commonly spend long periods lying still on the bottom (personal observation). It may be that they can receive the headwave signals produced by an air gun via bone conducted pathways. It is not known if they do this, nor if they did, what their response would be to the headwave component of an approaching air gun.

Fish response to air guns

The full methods and results describing the 10 fish trials carried out of the response of fish in a 10 x 6 x 3 m cage to a nearby operating air gun, are presented in McCauley et al (2000). The results included behavioural, physiological and pathological measurements from experimental trials and the running of a simple fish otolith model using air gun signals as the input to predict response. The experimental trials showed that the fish response to nearby air gun operations included:

- a startle response to short range start up or high level air gun signals;
- a greater startle response from smaller fishes and with an increase of received air gun level above 156–161 dB re 1 μPa rms;
- a lessening of severity of startle response through time (habituation);
- an increased use of the lower portion of cage during air gun operation periods;
- the tendency in some trials for faster swimming and formation of tight groups correlating with periods of high air gun levels;
- a general behavioural response of fish to move to bottom, centre of cage in periods of high air gun exposure (~ >156–161 dB re 1 μPa rms);
- a return to normal behavioural patterns some 14–30 minutes after air gun operations ceased;
- no significant physiological stress increases which could be attributed to air gun exposure; and
- for constrained fish, some preliminary evidence of damage to the hearing system of exposed fishes in the form of ablated and damaged hair-cells, although an exposure regime required to produce this damage was not established and it is believed such damage would require exposure to high level air gun signals at short range from the source.

The modelling work used a simple harmonic oscillator equation to model the otolith-macula relative movement, as described by de Vries (1950), Kalmijn (1988), Karlsen (1992) and Fletcher (1992) and using constants from various sources. This model only assumed the sound

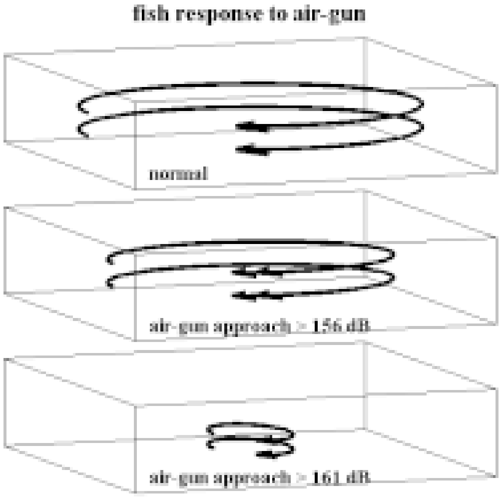

Figure 2. Generalised fish behavioural response to approaching air-gun. Units in dB re 1 mPa *rms*.

wave impinging directly onto the otolith system and did not include energy re-radiated from a nearby swimbladder or coupled to the otolith by mechanical linking from nearby gas bubble or swimbladder. Thus it is a first approximation and does not apply to hearing specialist fishes with morphological adaptations to enhance hearing sensitivity by adding in pressure reception. The model suggested that:

- above an air gun level threshold of around 171 dB re 1 µPa rms a fish otolith-macula system begins to show a rapid increase in absolute displacement parameters (displacement, velocity, acceleration), suggesting that associated behavioural response and susceptibility to mechanical damage will increase accordingly;
- smaller otoliths tracked the input air gun signal better than larger otoliths but showed lower absolute displacement parameters and returned to the rest position quicker, suggesting that smaller otolith systems may be at less mechanical risk from air gun exposure than larger ones; and
- the otolith system responded primarily to air gun energy <150 Hz, which encompassed the frequency of maximum energy of the input air gun signals.

The behavioural experiments were consistent in that with increasing air gun level some fishes persistently firstly increased swimming speed then moved to the lower portion of the cage then moved to 'huddle' in the cage centre. This general response is shown on Figure 2.

A similar response to that shown in Figure 2 has been widely reported for many fishes avoiding approaching vessels (Olsen et al, 1983; Ona 1988; Misund, 1993; or reviewed in Olsen 1990).

Pearson et al (1992) carried out trials exposing captive rockfish (*Sebastes* spp.) in a 4.6 m octagonal cage 3.6 m deep deployed at the water surface to signals produced by a 100 cui (1639 cm^3) air gun deployed at 6 m depth and operated at a 10 s rate. They observed similar behaviours to that described above, with *S. mystinus* milling in increasingly tighter schools with an increasing air gun level, *S. melanops* schools collapsing to the bottom when air gun operations started nearby and *S. miniatus* and *S. serranoides* schools remaining stationary near the bottom or rising in the water column on presentation of air gun signals. They gave received levels for subtle changes in behaviour of 161 dB re 1 µPa (mean-peak level, defined as dB value of mean of sum of maximum positive and absolute value of minimum negative pressure values) and for the 'alarm' responses (defined as general increases in activity and changes in schooling or position in the water column) at 180 dB re 1 µPa (mean-peak level).

Using conversion factors for the results presented here to mean-peak levels, gave levels for significant change in schooling behaviour from our experiments as 168–173 dB re 1 µPa mean–peak. This is lower than the level given for schooling changes given by Pearson et al (1992) of 180 dB re 1 µPa mean–peak, but lies within their range of 'subtle' behavioural changes at 161 dB re 1 µPa mean–peak, and their 'alarm' response at 180 dB re 1 µPa mean–peak. The lower levels of the 'alarm' responses reported here could be because of different behavioural definitions, species differences, the experiments reported here used fish acclimated to the cage over many days whereas the fish in the Pearson et al trials were captured by hook and line the day prior to the trial, or because the significant trials reported here used an approaching and departing air gun rather than a stationary one used in staircase fashion, as in the Pearson et al trials.

Despite the difference in levels required for similar behavioural changes between the two studies they are consistent in that at some received air gun level the fish behavioural state became altered significantly, to the point that they displayed what could be called the 'generic' fish alarm response of seeking shelter in tight schools near the bottom. Dalen and Raknes (1985) have also suggested that cod (*Gadus morhua*) may also respond to seismic signals by swimming towards the bottom.

Pearson et al (1992) recorded startle responses, defined as the C-turn type response (an involuntary response where all the lateral muscles along one side of the fish contract and the fish darts off in that direction, Blaxter et al 1981) at levels of 200 and 205 dB re 1 µPa mean-peak. In the trials reported here startle responses defined as faster and more erratic swimming, jerking movements concurrent with an air gun shot or flash expansion of schools became increasingly evident above 168 dB re 1 µPa mean-peak. The C-turn type responses were less common in the larger fishes at received levels up to 203 dB re 1 µPa mean-peak. But they were consistently observed from small (50–55 mm SL) *Pelates sexlineatus* between a received air gun level of 182–195 dB re 1 µPa mean-peak.

In a recent study, Wardle et al (in press) operated three 150 cui (2.5 L) air guns near a small reef system in Loch Ewe, Scotland. They observed fish behaviour through an underwater video system and movements of selected individuals using an ultrasonic pinger tracking system, for seven days before, during and for 4 days after air gun operations. Eight air gun exposures were used over a four day period. These ranged from 17 to 86 minutes in length with firing intervals of from 57–188 s. All exposures used a fixed air gun (constant range).

Wardle et al observed startle responses from fish in camera view for every air gun shot discharged, at levels from 195–219 dB re 1 μPa peak received at the observation camera. Again the units need conversion. The level at which C-turn responses were observed from the *P. sexlineatus* in the trials reported here was 183–196 dB re 1 μPa peak, which overlapped the bounds at which Wardle et al observed similar responses.

Wardle et al did not see any significant effect other than C-turn responses to each air gun shot. There was no shift in schooling behaviours of fish in the camera view and overall no significant change in the routine behavioural patterns of fish which transited the camera field of view or of those acoustically tracked, although there were some small aberrations. This may have been a function of the stationary air gun source and the low number of air gun shots discharged. The fastest repetition rate used was around once per minute which is much less than a conventional seismic survey of a shot every 5–15 s. The air gun was also fixed in position, unlike the typical rapidly increasing signal expected from an approaching air gun source. Thus the fact that Wardle et al did not see the generic fish 'alarm' response reported by Pearson et al (1992) or the increase in startle/alarm responses and 'huddling' behaviour seen with increasing air gun level described here, may have been an artefact of the exposure regime. The shot spacing may have been long enough for the fish to fully recover from the alarm response which initiated the C-turn, and the fact that the source was stationary meant it would not have constituted an approaching threat.

Thus, the behavioural results here and from other published works show some consistency and possibly predictability. Summarised, these are that at some received air gun level from an approaching vessel demersal fish could be expected to begin to change their behaviour by increasing speed and swimming deeper in the water column. As the air gun level increases these fishes would be expected to form compact schools probably near the bottom in continental shelf depths (<200 m). Eventually levels may be reached at which involuntary startle responses occur in the form of the classic C-turn. One would predict that at or near this level the fish would begin to show avoidance or for site attached fishes begin to seek refuge. Engas et al (1996) in an elegant and well carried out field trial in continental shelf waters, have displayed that avoidance by some species clearly occurs about an operating seismic vessel. In deeper water (> 200 m) any effects would be expected to lessen with increasing depth, as the air gun signal level dropped accordingly.

The threshold for the initial increases in swimming behaviour may be of the order of 156 dB re 1 μPa rms from the results presented here. For the 3D array measured (2678 cui in 100-120 m water depth) this corresponds to a range of around 3–5 km. At levels of around 161-168 dB re 1 μPa rms (results here and Pearson et al 1992 using conversion for Bolt air gun from mean–peak to rms units) active avoidance of the air gun source would be expected to occur. This corresponds to a range from the 3D array measured of 1–2 km. It must be cautioned that these ranges may differ depending on the specific air gun array and the local environment. For risk assessment these air gun level values can be used in exposure modelling to predict impacts for a specific survey and region, as described below.

The otolith modelling work carried out here showed that above an air gun level of approximately 171 dB re 1 μPa rms the response of the fish macula-otolith system increased dramatically. This suggested the behavioural response would increase accordingly. This is in line with the upper level prediction of avoidance of the air gun array.

The preliminary finding of pathological damage to the hearing system of pink snapper (*Chrysophrys auratus*) poses many questions. The fish used in trials were constrained and approached to short range with an operating air gun, unlike fish in the vicinity of a commercial operating seismic vessel. It could be expected that avoidance would occur before air gun signals reached levels sufficient to produce some form of hearing damage. The damage seen consisted of ablated or damaged hair cells on the maculae of the saggital otolith. Counts of ablated cells in exposed fishes were comparatively low (less than 1% of each sampling region of 23,500 μm^2 grid), although it was believed that ablated cells were indicative of wider damage to hair-cells which could not be easily quantified. It is known that fish can repair damaged hair cells (Lombarte et al, 1993). But it is not known how long this process takes nor how effective it is for given levels of damage. Samples were made here of repetitively exposed fish (46 days between exposures) and regularly through a recovery period up to 44 days after exposure, but at the time of writing these were still being worked up. At this stage these results must be considered as preliminary.

Although fish have been shown to survive very short range exposures to air gun noise (hence high levels) for periods up to several weeks after exposure, none of these experiments or conclusions have considered the fitness of the animal from the perspective of potential sub-lethal damage. The finding here of fish exposed to very short range air gun exposure exhibiting some damage to the hearing system, evident as ablated and damaged hair cells, implies that some fishes may have reduced fitness after exposure.

IMPLICATIONS OF SEISMIC OPERATIONS FOR FISHERIES

Commercial fisherman have long considered the operations of offshore seismic surveys to be disruptive to their fishery operations. This is not a phenomenon peculiar to any one country but is a view widely held by many fisherman across the world.

Engas et al (1996) have shown in an experimental regime that cod (*G. morhua*) and haddock (*Melanogrammus aeglefinus*) moved away from a 3 x 10 n mile region (5.6 x 18 km) in which seismic operations were carried out over a five-day period. They observed reductions in fish stock out to the limit of their sampling at 33 km. Løkkeborg (1991) analysed longline catches of cod *(G. morhua*) made in the presence of seismic surveys and concluded a reduction in catch rate had occurred, as did Skalski et al (1992) in an experimental trial with rockfish (*Sebastes spp*.). These observations suggested that the fish had responded in a fashion such that they either avoided the sound field of operating seismic vessels from some range or that their behavioural state was changed such that they were no longer available to the fishing techniques tested. Conversely, Løkkeborg and Soldal (1993) suggested that behavioural changes which forced fish to the bottom acted to temporarily increase catch rates of cod in saithe trawls during seismic activities. It should be noted that these studies have been undertaken in heavily fished regions and may not necessarily relate to Australian fisheries.

The literature observations support the findings presented here and justify the rationale on which the exposure modelling exercise was carried out. It is believed the threshold values used in the exposure modelling (161 and 166 dB re 1 µPa rms) will give a good indication of the level at which behavioural effects to nearby fish begin to occur. This form of model would be particularly useful for interpreting the scale and probability of the potential disturbance of a given seismic survey on finfish, in time and space. The interpretation of any disturbance then needs to be considered at the commercial fisheries level and at an ecological level. The ecological level would need to be species specific and consider factors such as spawning aggregations, the proportion of a population impacted upon and flow on effects to higher level predators. These issues are discussed further in McCauley (1994).

It must be pointed out that any potential seismic effects on fishes may not necessarily translate to population scale effects or disruptions to fisheries. For many fish species any behavioural changes or avoidance effects may involve little if any risk factor. Thus a thorough understanding of fish response to seismic, proper risk assessment procedures and good communication between seismic operators and fisherman can negate any potential or perceived problems.

Squid response to air guns

Three trials were carried out with caged squid (*Sepioteuthis australis*) to gauge their response to nearby air gun operations. In the first trial several squid showed a strong startle response to a nearby air gun starting up by firing their ink sacs and/or jetting directly away from the air gun source at a received level of 174 dB re 1 µPa rms. Throughout this trial the squid showed avoidance of the air gun by keeping close to the water surface at the cage end furthest from the air gun. The air gun level never fell below 174 dB re 1 µPa rms throughout this trial. During two trials with squid and using a ramped approach depart air gun signal (rather than a sudden nearby startup), the strong startle response was not seen but a noticeable increase in alarm responses were seen once the air gun level exceeded 156–161 dB re 1 µPa rms. No consistent avoidance responses were seen in these trials but there was a general trend for the squid to increase their swimming speed on approach of the air gun but then to slow at the closest approach and for them to remain close to the water surface during the air gun operations.

Squid were particularly capable of learning to associate the dinghy used to service the cage with feeding. They retained this association immediately after the cessation of air gun operations, coming to the dinghy to be fed, possibly indicating little hearing threshold changes.

Squid were the only animals observed during the caged trials which appeared to make use of the sound shadow near the water surface (an almost 12 dB difference was measured between hydrophones at 3 m and 0.5 m depth in trials 13 and 14 along the side of the cage). The fish generic response to the air gun was the opposite, to go towards the bottom which because of the sound propagation peculiarities would take them into the part of the water column with the highest levels of air gun signals.

The response of squid to air gun signals has not been reported in the literature before. They are an extremely important component of the food chain for many higher order predators, and sustain dedicated fisheries in some parts of the world. The responses seen in the cages suggest that like the other animals observed, behavioural changes and avoidance to an operating air gun would occur at some range. Thus, it is probable that seismic operations will impact upon squid and that the exposure modelling approach using thresholds at 161–166 dB re 1 µPa rms would give indications of the extent of disruption for specific seismic surveys.

General synthesis

Although many authors have stressed this point, it is reiterated here, there is as yet no standardised way to describe an impulsive air gun signal. This causes no end of confusion in comparing works from different authors and is easily capable of leading to erroneous conclusions by comparing different works with different unit systems. It was found here that the most consistent method to describe an air gun signal was some measure of its total energy reached above the background noise. It was found measurements which required time integration over the signal were prone to certain types of biases, which may or may not be present. It was also found that many factors may cause large differences in the received level of an air gun signal from the same source operating in the same general area. Thus air gun signal descriptors

Table 1. Summary of effects of nearby air-gun operations on a range of marine fauna from the literature and this study. Note all units are dB re 1 mPa *rms*. Where appropriate conversions have been applied from empirical measurement sets derived here. Superscripts: a - standoff range is minimum range animals allow operating vessel to approach; b - level derived from similar air-gun used in this study, see sea turtle section above; c - converted from mean-peak to *rms* using -12 dB correction from 7,712 records from Bolt 600B air-gun; d-correction of -12 dB applied (peak to *rms*), note that lower limit to elicit C turn not determined; e - exposure precisely known but because of ramped nature did not allow level for damage to be determined.

Source	**Level (dB re 1 mPa *rms*)**	**Animal group**	**Effects**
Malme et al 1985	160	gray whales	general standoff range
Richardson et al 1995	150–180	gray and bowhead whales	general standoff range—summary of many workers results
This study	157–164	humpback whales	standoff range for migrating humpbacks
This study	140	humpback whales	resting pods with cows in key habitat type begin avoidance
This study	143	humpback whales	resting pods with cows in key habitat type standoff range[a]
This study	179	humpback whales	maximum level tolerated by investigating probable male humpbacks to single air-gun, although this possibly due to visual clues
This study	166	green and loggerhead turtle	noticeable increase in swimming behaviour
This study	175	green and loggerhead turtle	turtle behaviour becomes increasingly erratic
O'Hara	[b]175–176	loggerhead turtle	avoidance
This study	156–161	various fin-fishes	common 'alarm' behaviour of forming 'huddle' on cage bottom centre, noticeable increase in alarm behaviours begins at lower level
Pearson et al (1992)	[c]149	rockfish (*Sebastes spp.*)	subtle behavioural changes commence
Pearson et al (1992)	[c]168	rockfish	alarm response significant
This study	> 171	fish ear model	rapid increase in hearing stimulus begins
This study	182–195	fish *P. sexlineatus*	persistent C-turn startle
Pearson et al (1992)	200–205	selected rockfish species	C-turn startle responses elicited
Wardle et al (in press)	[d]183–207	various wild finfish	C-turn startle responses
This study	146–195	various finfish	no significant physiological stress increase
This study	[e]????	fish *Chrysophrys auratus* and others	preliminary evidence of pathological damage to hearing systems of constrained fish
This study	174	squid	startle (ink sac fire) and avoidance to startup nearby
This study	156–161	squid	noticeable increase in alarm behaviours
This study	166	squid	significant alteration in swimming speed patterns, possible use of sound shadow near water surface

need to be precisely stated, the situations of the measurement stated and ideally conversions for that source in that environment into different units given.

A table of levels (in rms units) for various effects of nearby air gun operations on marine animals from literature and this study is given in Table 1. Despite the different animal groups listed there are some striking similarities in the thresholds for response to a nearby air gun. Several baleen whale species are listed as showing general avoidance of an operating seismic source at 150–164 dB re 1 µPa rms (excluding the resting cow pods from within Exmouth Gulf of this study), sea turtles were seen to begin to noticeably increase their swimming behaviour at 166 dB re 1 µPa rms, many fin-fishes displayed their general 'alarm' response of increased swimming speed, tightening schools and moving towards the sea floor at 156–168 dB re 1 µPa rms, and behavioural changes in squid were seen from levels of 156–166 dB re 1 µPa rms upwards. The hearing systems of baleen whales, sea turtles, fishes and squid are fundamentally different, yet the received air gun level range over which responses seem to become significant is within 18 dB for these diverse groups. This raises the questions:

- is there common evolutionary pressures which have shaped the high end hearing response of a wide range of marine animals; or
- is there a common limitation to the hearing systems of marine animals.

Although the mechanisms of delivering energy to the inner ear (or statocyst system of molluscs) may differ enormously, perhaps the limitations of hair-cell mechanics may shape the behavioural response to high intensity sounds.

ACKNOWLEDGEMENTS

The Australian Petroleum Production and Exploration Association (APPEA), initiated, sponsored and supported the work described here. APPEA is the national representative of the oil and gas industry in Australia.

For the first two years of the project the Australian Government organisation, the Energy Research and Development Corporation (ERDC), partially funded the project and managed the contract. Until a change of Government led to the abolition of the ERDC, the ERDC managed the Australian Federal Governments' direct investment in energy innovation. A number of petroleum exploration and development companies and other commercial groups have directly supported the project. These have included: Western Atlas; WMC Petroleum; Geco-Prakla; Shell Development Australia; Austal Ships; and the commercial aquarium Underwater World. An Australian Research Council (Industry) PhD. scholarship was obtained for expanding the scope of fish and squid trials. The WA Museum has assisted with taxonomy, while staff of Environment Australia, the Curtin University Animal Ethics Committee and the WA Conservation and Land Management assisted with appropriate permits. The following have contributed to the operation of the project: Doug Cato (Defence Science and Technology Organisation); Les Denison, Bronwyn Denison, Ann Smith and Mal Perry of the Centre for Marine Science and Technology; and Rebecca Donaldson, Michelle Dyer, Peter Mazzucato, Matthew Marshall, Ross McLaren-Nicole, Chris Burton, Ben Kennard, Chris Lally, Julie Castro, Elizabeth Howell, Sarah Dighton, Mandie Thompson, Paul Van Reekan and Steve Salmeri. This document and the full report on which it is based has benefited greatly from the constructive input of the reviewers: W.J. Richardson of LGL. Ltd, Canada; C. Greene of Greeneridge Sciences California; and A. Popper, University of Maryland.

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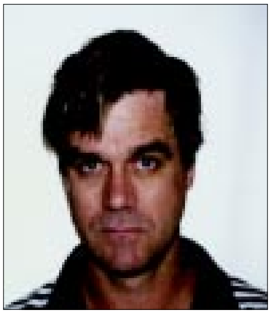
THE AUTHORS



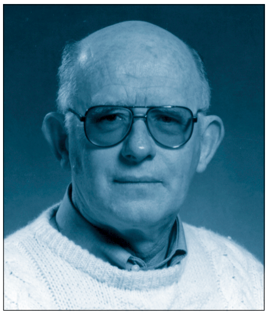
Robert McCauley has been a Research Fellow with the Centre for Marine Science and Technology of Curtin University since early 1996, after moving from James Cook University, Queensland where he held the position of associate lecturer. In 1986 he completed a BSc at James Cook University, and is completing a part-time PhD on the acoustic behaviour of tropical fishes. Rob has been working on the production, reception and ecology of Australian marine biological sea noise, and the effects of noise in the marine environment, since 1987.

Jane Fewtrell is completing a PhD on the effect of seismic survey noise on marine fish and invertebrates at Curtin University in the Aquatic Science Research Unit under the support of an APA(I) scholarship and APPEA. Jane completed a BSc (Biology, Hons) in1995 at Curtin University with the topic of her honours thesis the stress response of fish, focussing on fish involved in aquaculture. She was awarded a Neville Stanley Studentship in 1995, and spent 1996 managing the marine hatchery facility at Curtin University and conducting research into fish stress response in the live fish export industry.

Micheline-Nicole Jenner is a co-founder and principal investigator of the Centre for Whale Research (WA) Inc. She completed a BSc in Zoology in 1984 and an MSc in Marine Biology in 1987 from the University of Auckland. Micheline-Nicole has been studying whale populations since 1989, and since 1990 along with her partner Curt, has been studying humpback whales along the WA coast. Micheline's research focus is on humpback whale reproduction, life history, behaviour and pigmentation patterns.

Alec Duncan is a Senior Research Fellow with the Centre for Marine Science and Technology at Curtin University. He received a B App Sc from RMIT in 1979 and a Master of Applied Science degree from Curtin University in 1988. His main research interests are in marine acoustics, motions of surface and sub-surface vehicles and instrumentation. Member: IEEE, the Acoustical Society of America, the Australian Acoustical Society the Australian Institute of Physics.

Curt Jenner is a co-founder and Principal Investigator of the Centre for Whale Research (WA) Inc., which conducts studies on the population biology of humpback whales which frequent the WA coast. He gained a BSc from the University of Alberta, Canada, and is enrolled at the University of WA working towards an MSc on the population biology of humpback whales. Curt has been involved in field studies of whales since 1987, and since 1990 along with his partner Micheline-Nicole, has been studying humpback whales along the WA coast. Curt's research focus is on humpback whale population structure, population biology and migration patterns.



Prof. John Penrose is director of the Centre for Marine Science and Technology at Curtin University. He holds an Associateship in Applied Science from Perth Technical College and a PhD in Physics from City University, London. He is an Associate Editor of the Journal of Oceanic Engineering. Member: The Australian Institute of Physics, The Acoustical Society of America, the Institute of Electrical and Electronic Engineers Inc, and the Australian Acoustical Society.

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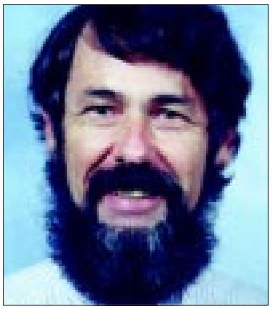

Robert I.T. (Bob) Prince has worked on nature conservation, wildlife and environmental management matters in Western Australian government agencies since 1969. He is presently a senior research scientist in the Department of Conservation and Land Management (CALM). After leaving school early to work in banking, he matriculated via external study and later completed BSc(Agric)(Hons) and PhD (Zoology) degrees from the University of Western Australia. Early work focused on the then very lively public issue of kangaroo management. In the marine sphere, WA dugong population studies were initiated independently in 1977. CALM has since assumed a greater formal involvement with dugong population surveys of this region commencing 1989. Regional sea turtle conservation work complementary to the earlier dugong and seagrass-ecosystem and environmental management focus, was developed through the Western Australian Marine Turtle Project (WAMTP), commencing 1986. Participatory engagement of external support for the WAMTP was actively sought and received from industry, community and the public.

Julie Murdoch is presently working with the Northern Territory Fisheries Department on biological assessment of fish stocks. She received her BSc. (ecology major) from Griffith University, Brisbane, and her MSc from James Cook University, Townsville, for research on the early life history of coral reef fishes. Julie is a marine ecologist, with research interests on the population dynamics of fishes, coral reef ecology and the conservation of marine resources.

Anita Adhitya is currently studying Science/Engineering at the University of Western Australia. Anita is presently in her third year of study, and expects to complete a BSc in 2000 with a major in physics.

Kathryn McCabe collaborates with the Centre for Whale Research (WA) Inc. Katie has completed an Associate Diploma of Applied Science majoring in Wilderness Reserves and Wildlife from Queensland University, and has an enormous depth of practical marine experience gained during her time on ocean-going sailing vessels throughout the world. She has a passionate interest in the biology and behaviour of humpback whales.