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July 2009

Potential Effects of Seismic Airgun Discharges on Monkfish Eggs (Lophius americanus) and Larvae

by

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ABSTRACT

Monkfish became a species of commercial importance with the decline in other fisheries resources in the early 1990's. It is fished on the east coast including in the area of the Laurentian Subbasin located off the south coast of Newfoundland. Seismic programs initiated in this area have drawn attention from the fishing industry regarding the potential for impacts on fisheries resources. Particular concern has been expressed about the potential for effects on developing monkfish eggs contained in large mucoid sheets or veils that float on the sea surface. Given the concern, the Environmental Studies Research Fund (ESRF) provided funds to the Fish Food and Allied Workers Union (FFAW) and Fisheries and Oceans Canada (DFO) to carry out a pilot exploratory study to address the concern. A laboratory approach was considered to be feasible given the high costs and challenging logistics of carrying out research of this nature in the field. It was initially recognized that one of the major challenges would be to find a veil or veils in the open sea.

Portions of veils were found and although they did not have eggs in an early stage of development, they contained eggs near hatch. Thus hatched larvae were used for the exposures. Seven separate trials (6 with 10 airgun discharges and 1 with 30) were carried out in which the sound pressure levels ~0.5 m below the surface container holding the larvae were ~205 dB peak to peak. No significant differences were observed between control and exposed larvae examined 48–72 hours post exposure.

Recognizing the possible difficulty of collecting a monkfish veil, it was decided early on that attempts should also be made to incorporate studies on capelin into the project. Thus pilot studies were also carried out with capelin eggs. Although artificial fertilization was poor, no significant differences in mortality were observed between control and capelin eggs exposed to seismic energy and examined 3 days post exposure to 20 airgun discharges. In this case, the sound pressure levels ~0.5 m below the container in which the slides were held were ~199 dB peak-to-peak. Other trials were carried out on capelin eggs exposed 1–3 days after fertilization and held for 9–10 days post exposure. Five separate trials were carried out and conditions were the same as for the monkfish larvae. Egg clumping precluded accurate counting of control and exposed eggs. However, live embryos could be resolved and were found to be present 9–10 days after exposure in all 5 trials and on all slides—experimental as well as control.

Modeling studies can be valuable for obtaining an appreciation (approximate estimates) of the transmission of seismic energy in the water column, but modeling of propagation in near surface waters presents special problems due to Lloyd's mirror effect (as well as waves). However models such as Kraken and Kraken C can provide rough estimates of plausible scenarios. Interestingly, the modeling studies that were carried out for a source level 250 dB at 1 m indicated a major attenuation of energy at the surface with a virtual pressure of nil when sediment was incorporated into the modeling. The modeled pressure levels were markedly below levels measured ~0.5 m under the monkfish larvae and capelin eggs in this study with no apparent mortality. Moreover, although literature is limited, the modeled levels were also orders of magnitude below levels reported in other studies to effect mortality in eggs and larvae.

Taking into consideration: (a) the results obtained on larval and egg exposures in this study, (b) modeled estimates of pressure levels at the water surface, and (c) literature on levels reported to effect mortality in eggs and larvae, it is unlikely that seismic surveys pose any real risk to either monkfish eggs or near hatch larvae that may float in veils on the sea surface during monkfish spawning.

RÉSUMÉ

Payne, J.F., Andrews, C.A., Fancey, L.L., Cook, A.L., and Christian, J.R. 2007.
Pilot study on the effect of seismic air gun noise on lobster (Homarus americanus).
Can. Tech. Rep. Fish. Aquat. Sci. 2712: v + 46.

La baudroie est devenue une espèce commerciale au début des années 1990 avec le déclin d'autres ressources halieutiques. Elle est pêchée sur la côte est, notamment dans la région du sous-bassin Laurentien, au large du littoral sud de Terre-Neuve. Les programmes sismiques amorcés dans la région ont attiré l'attention de l'industrie de la pêche en raison de l'impact potentiel sur les ressources halieutiques. On se préoccupe particulièrement des effets potentiels sur les œufs de baudroie qui se développent dans des nappes, ou voiles, mucoïdes flottant à la surface de la mer. Le Fonds pour l'étude de l'environnement (FÉE) a donc accordé un montant à l'Union des pêcheurs de Terre-Neuve et à Pêches et Océans Canada dans le but de mener une étude pilote préliminaire pour régler la question. L'étude en laboratoire a été privilégiée vu les coûts élevés et la logistique exigeante d'une recherche semblable menée in situ. Il a été admis au départ qu'une des principales difficultés consisterait à trouver un voile mucoïde en haute mer.

On a trouvé des parties de voile qui renfermaient des œufs non pas au stade initial de développement, mais prêts à éclore. Des larves écloses ont donc servi pendant les périodes d'exposition. Sept essais distincts (6 comptant 10 coups de canon à air et 1 en comptant 30) ont été effectués, au cours desquels la pression acoustique à approximativement 0,5 m sous le conteneur de surface renfermant les larves était d'environ 205 dB de crête à crête. Aucune différence importante n'a été observée entre l'échantillon témoin et les larves exposées, examinées de 48 à 72 h après l'exposition.

Compte tenu de la difficulté possible de trouver un voile de baudroie, il a été décidé dès le début qu'il faudrait aussi essayer d'incorporer au projet des études sur le capelan. Des études pilotes ont donc été menées également sur des œufs de capelan. Bien que la fécondation artificielle ait été faible, aucune différence importante n'a été observée dans le taux de mortalité entre l'échantillon témoin et les œufs de capelan examinés trois jours après avoir été exposés à 20 coups de canon à air. Dans ce cas, la pression acoustique, à peu près 0,5 m sous le conteneur renfermant les lames, était d'environ 199 dB de crête à crête. D'autres essais ont été effectués avec des œufs de capelan exposés un à trois jours après la fécondation et retenus pendant neuf ou dix jours après l'exposition. Cinq essais distincts ont été menés dans les mêmes conditions que pour les larves de baudroie. L'agglutination des œufs a empêché le comptage de l'échantillon témoin et des œufs exposés. Toutefois, des embryons vivants ont pu être détachés et étaient présents neuf ou dix jours après avoir été exposés, et ce dans les cinq essais et sur toutes les lames – aussi bien dans l'échantillon expérimental que dans l'échantillon témoin.

Les études de modélisation peuvent s'avérer utiles pour estimer la transmission d'énergie sismique dans la colonne d'eau, mais la modélisation de la propagation dans l'eau de surface avoisinante présente des problèmes particuliers en raison de l'effet de miroir de Lloyd (et des vagues). Cependant, les modèles comme Kraken et Kraken C peuvent

fournir des estimations très approximatives de scénarios plausibles. Chose intéressante, les études de modélisation effectuées pour un niveau d'émission de 250 dB à 1 m ont montré une importante atténuation d'énergie à la surface avec une pression virtuelle nulle lorsque des sédiments sont incorporés dans la modélisation. Les niveaux de pression modélisés étaient sensiblement inférieurs à ceux qui ont été mesurés à environ 0,5 m sous les larves de baudroie et les œufs de capelan dans cette étude, sans mortalité apparente. De plus, bien que la documentation soit limitée, les niveaux modélisés suivaient des ordres de grandeur inférieurs à ceux qui sont signalés dans d'autres études pour entraîner la mortalité parmi les œufs et les larves.

En tenant compte de ce qui suit : a) les résultats obtenus sur les larves et les œufs exposés dans cette étude; b) les niveaux de pression modélisés à la surface de l'eau et c) la documentation sur les niveaux signalés pour entraîner la mortalité parmi les œufs et les larves, il est peu probable que les levés sismiques posent un risque réel pour les œufs de baudroie ou les larves sur le point d'éclore qui flottent dans les voiles mucoïdes à la surface de la mer durant la période de frai.

INTRODUCTION

The Laurentian Subbasin located off the south coast of Newfoundland is an area of interest for petroleum exploration. In 2004, the Canada Newfoundland Offshore Petroleum Board announced exploration licences for the Subbasin and ConocoPhillips carried out seismic surveys in the area in 2004 and 2005.

A portion of the Subbasin is located within North Atlantic Fisheries Organisation (NAFO) fishing zone 3Ps and the fishing industry has raised concerns about the potential effects of seismic programs on fish and other marine life. Particular attention has been given to monkfish (Lophius americanus), a species about which little is known, but became a species of commercial importance with the decline in other fisheries resources in the early 1990's. Monkfish are unique in that egg development occurs in large extruded sheets or veils (often several metres in length) that may float in surface waters for a number of days or weeks (Scott and Scott, 1988). However, as for other life cycle characteristics, essentially nothing is known about this phenomenon in monkfish in Canadian east coast waters.

Given concerns about the potential effects of seismic surveys on developing eggs and larvae in surface waters, ESRF provided funds to the Fish Food and Allied Workers Union and Fisheries and Oceans Canada to carry out a pilot collaborative study to address the concern. A laboratory approach was considered to be feasible given the considerable costs and logistics of carrying out experiments of this nature in the field. Such a laboratory approach has been found useful in previous studies with lobster and snow crab (Payne et al, 2008, a, b).

It was recognized from the beginning that one of the first challenges was to find a veil in the open sea and preferably one with developing eggs localized "somewhere" in the large veil. Consultations with experienced monkfish harvesters determined that egg veils are usually seen on surface waters from around mid July to early August. Fishermen covered a wide area in July 2007, but no floating veils were observed. They were successful, however, in obtaining two unfertilized veils from freshly caught fish. These veils provided an opportunity for the research team and fishermen to learn about veil anatomy as well as procedures for holding veils at sea, transporting them to the laboratory and maintaining them under laboratory conditions—all of which were important for gauging veil decay or degradation times.

A brief overview of the protocol plan for veil collection and holding at sea is provided in Appendix 1 for general interest.

Fishermen carried out extensive searches again in July 2008 and were successful in obtaining portions of veils that had become entangled in fishing gear. Luckily, the portions contained developing eggs that were near the hatching stage. The veil portions were transported to the laboratory and maintained until airgun exposures were carried out on free swimming larvae.

Opportunistic pilot studies were also carried out on developing capelin eggs in both years.

MATERIALS AND METHODS

LARVAL MONKFISH EXPOSURES

Veil portions were delivered to DFO on two occasions in July 2008. Eggs were considered to be around stage 17, with fins, mouth and opercular opening and well developed eye pigment. The first veil contained a considerable quantity of near hatch larvae, while the container in which the second veil was delivered, contained upon arrival a quantity of hatched as well as near hatch larvae. Veil portions as well as any free swimming larvae were held in a flow through aquarium until exposures were carried out. All exposures were carried out with hatched larvae.

Larvae from veil number one were used in the first three exposures (1–3), while the remaining exposures (4–8) were carried out with larvae from veil number two. Larvae were placed in 1,000 ml polypropylene bottles for exposures 1–5 and 7 and in 500 ml polyethylene bags for exposures 6–8. Approximately 25 larvae were used per exposure.

Exposures were carried out in a flow through aquarium, 4.72 m in length, 2.59 m in width and 1.10 m in depth. Containers with larvae were submerged approximately 1–2 cm below the surface and 10 discharges were fired 10 seconds apart, except for exposure 8, which received 30 discharges. Exposures were carried out with a 20 cubic inch sleeve gun placed approximately 1.5 m from the larvae. Sound pressure levels were recorded with a hydrophone placed vertically under the larvae at a distance of approximately 0.5 m.

Hydrophone specifications were as follows: Manufacturer: Reson; Model: TC 4014; usable frequency range: 15Hz–480 kHz; horizontal directivity pattern: omni directional; vertical directivity pattern: 270 deg +/-2dB at 100 kHz receiving sensitivity: -186dB +/-3 dB operating depth: 900 m.

Control larvae were treated in the same manner except no airgun exposures were carried out. Upon exposure, larvae were transferred to 1,000 ml glass beakers that were placed in a bath at ambient seawater temperature.

Observations were carried out on larvae 24 and 48 hrs post exposure with some trials being carried through to 72 and 96 hrs.

CAPELIN EGG EXPOSURES

Pilot feasibility studies were also carried out to determine whether capelin eggs adhered to glass slides could be artificially fertilized with the slides subsequently being exposed to airgun discharges and examined a number of days post exposure for change in egg mortality or, for instance, major alteration in development.

Fertilization trials were first carried out on capelin collected from Bellevue Beach, Trinity Bay in mid July 2007. The procedure was as follows: eggs were gently stripped from a female (F1) and attached to a dry glass microscope slide along a line down the middle of the slide. Milt from 3 males was likewise stripped into a Coplin jar containing seawater and the slides with attached eggs were incubated in the jar for 5 minutes. The jar was kept cool in a bath of seawater. The procedure was repeated with the same female to produce 4 slides. Slides were then prepared from 4 other females (F2–F5) in the same manner, producing 20 slides in total.

Upon incubation, the slides were placed on top of a layer of beach sediment in a cooler containing clean seawater and transported to the laboratory. Slides were kept in the cooler with running seawater at ambient temperature (~9–10°C) until exposure.

Exposures were carried out 6 days after fertilization. Slides were arranged inside two wire mesh baskets (0.15 m x 0.15 m x 0.15 m) lined with 330 µ Nitex mesh. The slides were attached to the sides of the wire mesh baskets inside the Nitex liner with clips. One basket contained the control slides and the other the seismic exposed slides. The slides were arranged down two sides of each basket with 5 slides on a side for a total of ten slides. The exposure basket was oriented with the outside corner of the basket facing away from the airgun so no slide would be side-on to the exposure. This allowed the "open V-shape" of the basket corner to be oriented towards the airgun. The basket was lowered into the exposure tank with the top of the basket held just below the surface of the water.

The exposures in 2007 were carried out with a GI-gun in a circular aquarium, 5 m in diameter and 1.2 m in height. The gun was placed approximately 2.5 m from the larvae with the hydrophone positioned just below the basket. Eggs were exposed to 20 discharges, 10 seconds apart. The control basket was treated in the same manner without exposures being carried out.

The slides were preserved in 10% formalin 3 days post exposure. Each slide was examined microscopically (40x magnification) with counts being made on the number of eyed eggs per 250–300 eggs examined. Eggs alive at the time of fixation remained transparent while the dead eggs turned opaque.

A similar pilot trial was carried out on capelin eggs in 2008, except at this time the exposures were carried out under the same conditions as used in the trials with monkfish larvae.

SOUND METRIC MODELING

The Kraken and Kraken C models based in part upon Porter and Reis (1984) were used to obtain an estimate of pressure levels received at the surface assuming a peak-to-peak signature of 250 dB re 1 µ Pa at 1 m.

Physical properties of the water column for model simulations were extracted from a Web based Generalized Digital Environmental Model (GDEM) (a global climatology of the temperature, salinity, temperature standard deviation, and salinity standard deviation of the global oceans developed by the US Naval Oceanographic Office) and correspond to average conditions at a point on St. Pierre Bank in two contrasting months of the year.

Depth of the averaged node in the GDEM database was 50 m. In order to extend the reach of the simulations, temperature and salinity values for 50 m were repeated at hypothetical depths of 100 m, 200 m and 300 m. The speed of sound was recalculated to account for the new pressure values at these depths.

Root–mean-squared pressure (RMS) levels are reported for simulations. For the same airgun array, peak-to-peak pressure values are always higher than RMS values. The relationship between these two magnitudes is complex and depends on many physical, engineering and environmental variables. Field studies have been carried out allowing the establishment of certain approximate equivalences between both magnitudes. McCauley et al. (2003) indicate that a source level of 222 dB re 1 μ Pa (p-p) corresponds to an RMS level of about 203 dB re 1 μ Pa. On the other hand, Cummings (2003) reported that for an airgun in the open ocean, p-p values average about 15 dB higher than RMS values. In the simulations presented here, received levels referred to are RMS levels and are assumed to be 15 dB lower than the corresponding peak-to-peak levels.

The transmission losses were calculated using AcTUI (V. 1.6), a front end MATLAB implementation of the Acoustic Toolbox developed by Mike Porter (http://www.hlsresearch.com/oalib/Modes/AcousticsToolbox/). AcTUI was developed by Alec Duncan of the Center for Marine Science and Technology, Curtin University of Technology, Australia.

(http://www.cmst.curtin.edu.au/products/actoolbox/archive1_6.html).

Airguns have a very wide frequency spectrum (~20 Hz to ~400 Hz) and because the propagation is frequency dependent, it is necessary to resolve the received sound levels for relatively narrow frequency bands. In this case, the frequency spectrum was divided into 1/3 octave frequency bands, for which the centre frequencies (Hz) are: 25, 31, 40, 50, 63, 80, 100, 125, 160, 200, 250, 315, 400 and 500. The propagation code was run at these centre frequencies, and then the result for all the bands was combined to obtain the total received levels.

RESULTS

SOUND METRICS

Representative metrics obtained for the tank (4.72 m in length x 2.59 m in width x 1.10 m in depth) in which the monkfish larvae and capelin eggs were exposed in 2008 are given in Table 1. Sound levels were recorded with the hydrophone placed vertically under the larvae at a distance of ~0.5 m and mean peak-to-peak sound pressure levels were ~205 dB re 1µ Pa. Representative metrics obtained for the tank (5 m in diameter x 1.2 m in depth) in which capelin eggs were exposed in 2007 are given in Table 2 and mean peak-to-peak sound pressure levels were ~199 dB re 1µ Pa.

TABLE 1. REPRESENTATIVE SOUND METRICS: MONKFISH LARVAE AND CAPELIN EGGS (SLEEVE GUN IN RECTANGULAR TANK, 2008)

SPL-P-P (dB re 1µ Pa)	SPL-P (dB re 1µ Pa)	SPL-RMS (dB re 1µ Pa)	EDS Peak (dB re 1µ Pa2/Hz)	Frequency (Hertz)	P Velocity (dB re 1nm/s)
205.3	200.4	176.7	147.8	13.2	126.6
204.8	199.6	176.7	147.2	13.2	115.5
205.3	200.4	176.5	146.3	13.2	127.2
205.2	200.2	177.1	146.3	13.2	131.2
205.1	200.1	176.5	144.0	13.2	124.4
205.2	200.2	176.4	146.6	13.2	138.4
204.7	199.3	175.7	146.1	13.2	125.9
204.9	199.8	175.8	146.4	13.2	90.6
205.3	200.4	175.6	145.9	13.2	133.7
205.0	199.9	175.6	146.6	13.2	121.8
Mean					
205.1	**200.0**	**176.3**	**146.3**	**13.2**	**123.5**

(dB re 1µ Pa) = Decibels re 1 Micro Pascal
SPL-P-P = Sound Pressure Level– Peak to Peak
SPL-P = Sound Pressure Level–Peak
SPL-RMS = Sound Pressure Level–Root Mean Squared
EDS Peak = Energy Density Spectrum–Peak
P Velocity = Particle Velocity

TABLE 2. REPRESENTATIVE SOUND METRICS: CAPELIN EGGS (GI GUN IN CIRCULAR TANK, 2007)

SPL-P-P (dB re 1μ Pa)	SPL-P (dB re 1μ Pa)	SPL-RMS (dB re 1μ Pa)	EDS Peak (dB re 1μPa²/Hz)	Frequency (Hertz)	P Velocity (dB re 1nm/s)
199.35	190.70	167.03	166.60	18.31	134.42
198.90	192.35	167.16	167.93	18.31	135.90
198.01	190.30	167.24	170.24	18.31	135.80
199.35	191.79	167.39	172.18	19.84	134.96
198.54	193.01	167.00	170.97	19.84	134.11
198.94	193.03	167.10	171.52	19.84	135.08
199.29	192.07	164.34	171.90	19.84	134.09
199.09	190.51	164.08	171.29	19.84	137.38
197.42	191.27	164.00	171.58	19.84	136.50
199.29	192.07	161.88	158.68	24.41	135.00
Mean					
198.82	**191.71**	**165.72**	**169.29**	**19.84**	**135.32**

(dB re 1μ Pa) = Decibels re 1 Micro Pascal
SPL-P-P = Sound Pressure Level–Peak to Peak
SPL-P = Sound Pressure Level–Peak
SPL-RMS = Sound Pressure Level–Root Mean Squared
EDS Peak = Energy Density Spectrum–Peak
P Velocity = Particle Velocity

MONKFISH LARVAE EXPOSURES

Six trials were carried out in which monkfish larvae were exposed to 10 discharges at received levels of ~205 dB peak-to-peak, ~0.5m below the larvae (Tables 3–8). Observations were carried out after various time periods on the numbers of "dead/morbid" versus live larvae occurring in the control and experimental groups. A few motionless larvae lying on the bottom of a container and classified as "dead/morbid" in one time period could appear in the water column in a subsequent period and thus be classified as alive. Also, larval movement in the water column sometimes precluded highly accurate counting of live larvae. No statistically significant differences were found (e.g., P values < 0.05 by Fisher exact test) between the control and exposed larvae at any time period in any of the trials.

TABLE 3. EXPOSURE 1 – MONKFISH LARVAE VEIL #1

Post Exposure Time	Observations	Control Group	Exposed Group	P-Value[a]
24 hours	Dead/Morbid	0	1	0.405
	Alive	25	16	
48 hours	Dead/Morbid	1	1	1.000
	Alive	24	16	
72 hours	Dead/Morbid	1	2	0.556
	Alive	24	15	

10 exposures, 10 seconds apart

[a] P-Value using Fisher exact test

TABLE 4. EXPOSURE 2 – MONKFISH LARVAE VEIL #1

Post Exposure Time	Observations	Control Group	Exposed Group	P-Value[a]
24 hours	Dead/Morbid	0	5	0.492
	Alive	26	27	
48 hours	Dead/Morbid	1	4	0.355
	Alive	25	25	
72 hours	Dead/Morbid	1	4	0.335
	Alive	25	25	

10 exposures, 10 seconds apart

[a] P-Value using Fisher exact test

TABLE 5. EXPOSURE 3 – MONKFISH LARVAE VEIL #2

Post Exposure Time	Observations	Control Group	Exposed Group	P-Value[a]
24 hours	Dead/Morbid	7	1	0.121
	Alive	26	23	
48 hours	Dead/Morbid	7	3	0.494
	Alive	27	22	

10 exposures, 10 seconds apart

[a] P-Value using Fisher exact test

TABLE 6. EXPOSURE 4 – MONKFISH LARVAE VEIL #2

Post Exposure Time	Observations	Control Group	Exposed Group	P-Value[a]
24 hours	Dead/Morbid	0	0	1.000
	Alive	26	27	
48 hours	Dead/Morbid	1	1	1.000
	Alive	24	24	

10 exposures, 10 seconds apart

[a] P-Value using Fisher exact test

TABLE 7. EXPOSURE 5 – MONKFISH LARVAE VEIL #2

Post Exposure Time	Observations	Control Group	Exposed Group	P-Value[a]
24 hours	Dead/Morbid	0	1	1.000
	Alive	31	31	
48 hours	Dead/Morbid	2	2	1.000
	Alive	28	34	
72 hours	Dead/Morbid	4	3	0.691
	Alive	24	31	

10 exposures, 10 seconds apart

[a] P-Value using Fisher exact test

TABLE 8. EXPOSURE 6 – MONKFISH LARVAE VEIL #2

Post Exposure Time	Observations	Control Group	Exposed Group	P-Value[a]
24 hours	Dead/Morbid	0	1	0.443
	Alive	34	26	
48 hours	Dead/Morbid	0	3	0.081
	Alive	34	24	
72 hours	Dead/Morbid	4	3	0.697
	Alive	26	31	
96 hours	Dead/Morbid	6	12	0.265
	Alive	24	22	

10 exposures, 10 seconds apart

[a] P-Value using Fisher exact test

TABLE 9. EXPOSURE 7 – MONKFISH LARVAE VEIL #2

Post Exposure Time	Observations	Control Group	Exposed Group	P-Value[a]
24 hours	Dead/Morbid	0	0	1.000
	Alive	30	30	
48 hours	Dead/Morbid	0	0	1.000
	Alive	30	30	
72 hours	Dead/Morbid	3	2	1.000
	Alive	27	28	
96 hours	Dead/Morbid	6	3	0.309
	Alive	24	27	

10 exposures, 10 seconds apart

[a] P-Value using Fisher exact test

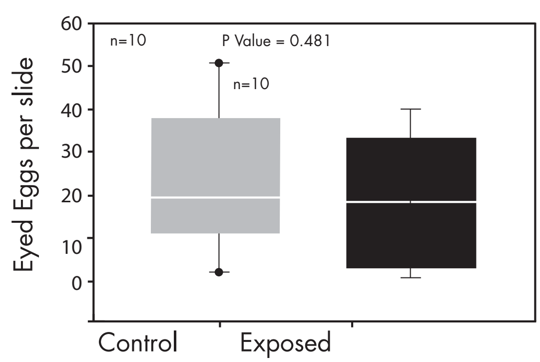
One trial was carried out in which larvae were exposed to 30 discharges instead of 10 (Table 9). Again, no statistically significant difference in survival was found between the control and exposed larvae up to a post-exposure period of 96 hours.

CAPELIN EGGS

It was decided early on that in the event of lack of success in collecting monkfish eggs, and subject to availability, backup trials would be attempted on capelin eggs (or larvae) that would be exposed at the surface in the same manner as planned for monkfish. A pilot feasibility study was carried out to determine whether capelin eggs adhered to glass microscope slides could be artificially fertilized, exposed and successfully incubated for a number of days post exposure in order to obtain counts on live eggs—the anticipated problem being the potential for fungal, bacterial or nematode infections to occur, should the slides contain (from the beginning) large numbers of dead eggs resulting from poor fertilization.

Eggs fertilized in the field were exposed at received levels of ~199 dB peak-to-peak, ~0.5m below the eggs, nine days after fertilization and left to develop for a further 3 days at which time they were fixed for examination. Counts were carried out on the number of eyed eggs per 250–300 eggs examined per slide. Overall, fertilization success was poor but no statistical difference in eyed egg numbers was found between the control and the exposed group (Figure 1).

Figure 1.
Exposure of capelin eggs (20 discharges) with GI gun in circular tank.



250-300 eggs in total were counted per slide. Data plotted are medium, 10th, 25th, 75th and 90th percentiles as vertical boxes with error bars. Data points beyond the 5th and 95th percentiles ar also displayed. Comparison of medians, P value by t-test.

Similar trials were also carried out in 2008 in which eggs were exposed at received levels of ~205 dB peak-to-peak, ~0.5 m below the eggs. The trials involved 5 different egg collections with exposures being carried out shortly after fertilization (within 1–3 days). The trials met with poor fertilization success and this coupled with egg clumping precluded accurate counts of either control or exposed groups. However live embryos could be resolved and were found to be present 9–10 days after exposure in all 5 trials and on all slides—experimental as well as control (Table 10).

TABLE 10. EFFECT OF SEISMIC EXPOSURE ON DEVELOPING CAPELIN EGGS

Study	Exposure (days post fertilization)	Examination (days post fertilization)	Live Embryos	
			Control	Exposed
1	1	8	Slide 1 + Slide 2 + Slide 3 + Slide 4 +	Slide 1 + Slide 2 + Slide 3 + Slide 4 +
2	1	9	Slide 1 + Slide 2 + Slide 3 + Slide 4 +	Slide 1 + Slide 2 + Slide 3 + Slide 4 +
3	1	10	Slide 1 + Slide 2 + Slide 3 + Slide 4 +	Slide 1 + Slide 2 + Slide 3 + Slide 4 +
4	2	9	Slide 1 + Slide 2 + Slide 3 + Slide 4 +	Slide 1 + Slide 2 + Slide 3 + Slide 4 +
5	3	10	Slide 1 + Slide 2 + Slide 3 + Slide 4 +	Slide 1 + Slide 2 + Slide 3 + Slide 4 +

Exposure of capelin eggs (10 discharges) with sleeve gun in rectangular tank. + Denotes presence of live embryos.

SUMMARY FOR LARVAL AND EGG STUDIES

No statistical differences in mortality were found between control and exposed monkfish larvae in any of the trials in which sound pressure levels ~0.5 m below the larvae were ~205 dB peak-to-peak. This included one trial in which the larvae were exposed to 30 discharges instead of 10. Note that thirty shots is relatively high in relation to a seismic ship traveling 4–5 knots and discharging every 25–50 meters. Although fertilization success was poor, similar results were obtained with developing capelin eggs.

Sound has both pressure and particle velocity components and at close range particle velocity could predominate over pressure (e.g., Lugli and Fine, 2007). Although particle motion may have little or no potential for causing or influencing acute mortality, it is at least known that fish can detect particle motion (e.g., Popper and Fay, 1973). Thus, even though the eggs and larvae in our exposures may have been subjected to greater particle velocity than under field conditions, no effects were observed.

Regarding previous investigations, a few studies have been carried out on the effects of seismic energy on finfish eggs and larvae. These studies have been reviewed (Payne, 2004). Where observed, larval mortality has generally been associated with much higher pressure levels than measured in this study. They are also orders of magnitude higher than pressure levels calculated for surface waters from modeling studies (see below).

MODELING

Acoustic propagation modeling and the search for agreement between observed and predicted sound levels is continually evolving (e.g., Cochrane, 2007; Carr and Erbe, 2008) and any modeling studies carried out in relation to a nearby source and directed towards the water surface has special drawbacks. This is in part due to Lloyd's mirror effect, whereby a sound source just below the surface generates constructive and destructive interferences (e.g., Richardson et al., 1995; DeRuiter et al., 2006). However, using one of the transmission loss models to give received levels for a single airgun is suitable for providing a first cut estimate. Kraken and Kraken C are both normal mode models. Kraken estimates sound attenuation but is not accurate at short ranges since it can only account for energy that is trapped in the wave guide and misses the short term range areas where the untrapped energy is significant. Kraken C, on the other hand, tries to calculate normal modes in the complex wave number plane, which allows for more accurate calculation of untrapped energy at close ranges.

Because of the potential influence of the seabed character in the trials, two scenarios were considered: a bottom made up of bare rocks and a rocky bottom covered by a sediment layer of fine sand. Louden (2002) provides a characterization of bottom sediment thickness off the Atlantic coast of Canada. In the area south of Newfoundland, the sediment layer is relatively shallow, with a thickness of around or less than 500 m.

These two scenarios were conceived with the goal of creating credible bottom conditions for "maximum" and "minimum" underwater sound propagation scenarios. Thus, the working hypothesis was that for the given source level, the actual received levels should be somewhere between the maximum and minimum scenarios presented. Simulations were run using different models under contrasting water column and bottom conditions.

Among the received levels obtained from all the resulting combinations, the Kraken normal mode model (Porter and Reiss, 1984) used without a bottom sediment layer produced the highest levels at pre-established control ranges. The KRACKEN C model with a bottom sediment layer thickness of 500 m showed the lowest received levels for the control ranges. The results from these two simulation configurations were selected to represent the maximum scenario and the minimum scenario, respectively.

Results of the simulations are presented in Tables 11 to 18. They summarize the model output for the maximum and minimum propagation scenarios, for a winter-like and a summer-like water density profile, and for a flat bottom located 100 m and 200 m deep.

TABLE 11. RECEIVED LEVELS (DB RMS) FOR A KRAKEN SIMULATION WITHOUT BOTTOM SEDIMENT IN WINTER FOR A FLAT BOTTOM 100 M DEEP

	Range (m)				
Depth (m)	**20**	**121**	**322**	**625**	**1,028**
0	111	111	109	103	105
20	206	206	197	196	194
40	207	207	201	198	195
60	208	208	203	199	194
80	206	206	201	199	197
100	207	207	203	201	197

TABLE 12. RECEIVED LEVELS (DB RMS) FOR A KRAKEN SIMULATION WITHOUT BOTTOM SEDIMENT IN WINTER FOR A FLAT BOTTOM 200 M DEEP

	Range (m)				
Depth (m)	**20**	**121**	**322**	**625**	**1,028**
0	116	116	114	112	110
20	206	206	192	190	191
40	207	207	196	190	192
60	208	208	198	193	192
80	206	206	198	195	191
100	203	203	198	197	194
150	193	193	199	196	193
200	191	191	202	197	192

TABLE 13. RECEIVED LEVELS (DB RMS) FOR A KRAKEN SIMULATION WITHOUT BOTTOM SEDIMENT IN SUMMER FOR A FLAT BOTTOM 100 M DEEP

	Range (m)				
Depth (m)	**20**	**121**	**322**	**625**	**1,028**
0	124	124	129	118	120
20	205	205	198	197	195
40	207	207	199	196	194
60	207	207	199	195	194
80	206	206	201	196	193
100	206	206	204	197	196

TABLE 14. RECEIVED LEVELS (DB RMS) FOR A KRAKEN SIMULATION WITHOUT BOTTOM SEDIMENT IN SUMMER FOR A FLAT BOTTOM 200 M DEEP

	Range (m)				
Depth (m)	**20**	**121**	**322**	**625**	**1,028**
0	127	127	121	123	119
20	205	205	184	191	193
40	206	206	190	191	193
60	207	207	194	192	193
80	206	206	197	192	192
100	202	202	199	194	190
150	193	193	199	194	189
200	191	191	202	198	190

TABLE 15. RECEIVED LEVELS (DB RMS) FOR A KRAKEN C SIMULATION WITH BOTTOM SEDIMENT IN WINTER FOR A FLAT BOTTOM 100 M DEEP

	Range (m)				
Depth (m)	**1**	**102**	**304**	**596**	**1,000**
0	21	11	4	3	-2
20	191	181	176	171	171
40	193	184	176	174	171
60	194	184	178	175	174
80	193	183	179	175	173
100	183	175	172	168	166

TABLE 16. RECEIVED LEVELS (DB RMS) FOR A KRAKEN C SIMULATION WITH BOTTOM SEDIMENT IN WINTER FOR A FLAT BOTTOM 200 M DEEP

	Range (m)				
Depth (m)	**1**	**102**	**304**	**596**	**1,000**
0	24	13	13	12	10
20	199	189	184	180	176
40	191	181	178	177	177
60	189	179	175	174	174
80	188	178	174	171	169
100	191	181	174	172	172
150	189	177	173	169	167
200	191	191	202	198	190

TABLE 17. RECEIVED LEVELS (DB RMS) FOR A KRAKEN C SIMULATION WITH BOTTOM SEDIMENT IN SUMMER FOR A FLAT BOTTOM 100 M DEEP

	Range (m)				
Depth (m)	**1**	**102**	**304**	**596**	**1,000**
0	-3	-13	-18	-21	-23
20	185	178	167	168	166
40	182	174	170	164	163
60	184	174	170	167	165
80	184	174	170	169	165
100	187	176	173	169	166

TABLE 18. RECEIVED LEVELS (DB RMS) FOR A KRAKEN C SIMULATION WITH BOTTOM SEDIMENT IN SUMMER FOR A FLAT BOTTOM 200 M DEEP

	Range (m)				
Depth (m)	**1**	**102**	**304**	**596**	**1,000**
0	8	-2	-7	-10	-12
20	179	174	160	155	154
40	168	165	157	145	149
60	165	161	160	146	151
80	166	157	161	147	152
100	169	157	159	151	152
150	164	155	153	155	154
200	191	191	202	198	190

Graphical representations of the model results including for a depth of 300 m as well as 100 m and 200 m are found in Appendix 2. Received levels are not predicted values to be expected in real conditions in any geographical area. They should be seen as plausible scenarios of underwater sound propagation for the given environmental conditions and source characteristics. However, for the purpose of this project, which was to provide information on potential risks to monkfish eggs floating at the surface in the near vicinity of seismic programs, it is important to note that the modeling studies indicate major attenuation at the surface. For instance, the received levels at the surface for a flat bare rock bottom, 100–200 metres in depth were generally less than 130 dB RMS or ~145 dB peak-to-peak. In the meantime, the received levels at the surface for a rocky bottom covered with sand were even much lower, being essentially nil in summer.

Further, Caldwell and Dragoset (2000) note that the real acoustic pressure values encountered in the immediate vicinity of airgun arrays are usually less than the back-calculated, far-field estimated values, which points to the conservative character of propagation predictions based on these parameters. Therefore, the levels are probably larger than the most likely received levels to be measured under similar circumstances.

It is of interest to compare the modeled levels for the sea surface and to which eggs or larvae might be exposed with other sources of noise in the ocean. Richardson et al. (1995) noted that source levels in the strongest 1/3 octave band range from 150–160 dB re 1 μ Pa for outboards and other small boats to at least 185–200 dB for tankers and large container ships. Moreover, boats and ships often emit sound at low frequencies similar to airguns.

CONCLUSIONS

A pilot study was carried out to investigate the potential for seismic programs to effect mortality/morbidity in monkfish eggs, which are often found in large mucoid veils floating at the sea surface. Portions of veils were found and, although they did not have eggs in an early stage of development, they contained eggs near hatch; thus hatched larvae were used for the exposures. No significant differences were observed between control and exposed larvae examined 48 hours post exposure to seismic energy. Seven separate trials were carried out and the sound pressure levels ~0.5 m below the surface container holding the larvae were ~205 dB peak-to-peak.

Pilot studies were also carried out with capelin eggs. Although success with artificial fertilization was poor, no significant differences in mortality were observed between control and capelin eggs exposed to seismic energy and examined 3 days post exposure. In this case the sound levels below the container were ~199 dB peak-to-peak. Other trials were carried out on capelin eggs exposed 1–3 days after fertilization and held for 9–10 days post exposure. Five separate trials were carried out and conditions were the same as for the monkfish larvae. Egg clumping precluded accurate counting of control and exposed eggs. However, live embryos could be resolved and were found to be present 9–10 days after exposure in all 5 trials and on all slides—experimental as well as control.

Modeling studies can be valuable for obtaining an appreciation of the transmission of seismic energy in the water column, but modeling of propagation in near surface waters presents problems due to Lloyd's mirror effect (as well as waves). However models such as Kraken and Kraken C can provide rough estimates of plausible scenarios. Interestingly, the modeling studies that were carried out indicated a major attenuation of energy at the surface with a virtual pressure of nil when sediment was incorporated into the modeling. The modeled levels were markedly below levels measured ~0.5 m under the monkfish larvae and capelin eggs in the study. Moreover, although literature is limited, the modeled levels also were orders of magnitude below levels reported to effect mortality in eggs and larvae.

Taking into consideration (a) the results obtained on larval and egg exposures in this study, (b) the modeled estimates of pressure levels at the water surface, and (c) literature on levels reported to effect mortality in eggs and larvae, it is unlikely that seismic surveys pose any real risk to either monkfish eggs or near hatch larvae floating at the sea surface.

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We also wish to thank Hugh Bain and Ken Lee for their continuing support through the COOGER office.

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APPENDIX 1

Protocol Plan For Veil Collection

A collection protocol for the at-sea collection and holding of monkfish egg veils was developed by FFAW and DFO and reviewed by the ESRF Technical Advisory Committee (TAG). DFO provided training sessions for five FFAW technicians. Training included familiarization with project objectives and identification of egg stage development through the use of capelin eggs. FFAW selected fishing vessels that would participate in the project during regular fishing trips for monkfish. Prior to vessel departure, FFAW briefed the captain and crew on their responsibilities:

- In conjunction with onboard FFAW technicians, be continuously on the lookout for veils while on deck and on watch;
- Turn off all bilge pumps when in the near vicinity of a veil;
- Retrieve stabilizer "fish" while an egg veil is being collected to prevent damage;
- Carefully approach a veil on the starboard side of the vessel;
- Help the technician to gently remove the veil from the surface with a large dip net and slowly hoist the net onboard and into a large aerated receiving tank;
- Facilitate communication of "Daily Reports" to shore by FFAW technicians;
- Protect and monitor the condition of the veils until they are delivered to port where appropriate FFAW and/or DFO personnel will take charge of the veils and transport them to DFO.

Regarding the fishing vessels, FFAW verified that the vessels met all navigational and safety equipment requirements established for commercial fishing vessels (for their category) by DFO, the Canadian Coast Guard, Transport Canada and/or the RCMP. Each vessel sailed with experimental licences provided by DFO.

APPENDIX 2
GRAPHICAL REPRESENTATION OF MODEL RESULTS

1. KRAKEN RUNS WITH NO SEDIMENT BOTTOM

Figure 1.1.
Received levels vs. depth at different ranges. KRAKEN results. Winter 100 m depth.

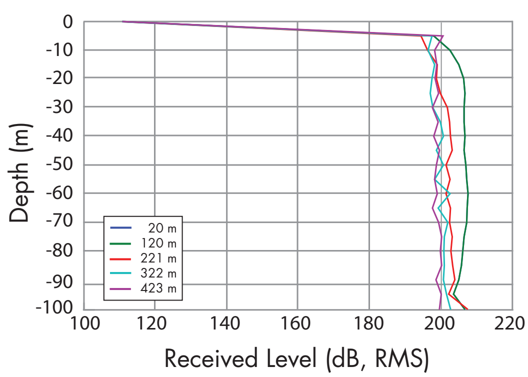


Figure 1.2.
Received levels vs. depth at different ranges. KRAKEN results. Winter 200 m depth.

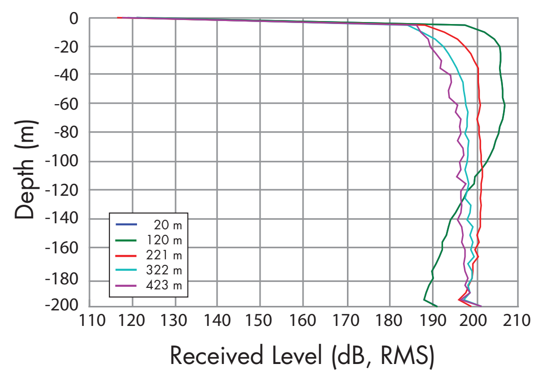


Figure 1.3.
Received levels vs. depth at different ranges. KRAKEN results. Winter 300 m depth.

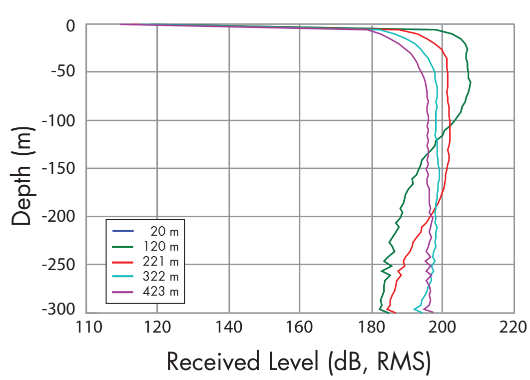


Figure 1.4.
Received levels vs. depth at different ranges. KRAKEN results. Summer 100 m depth.

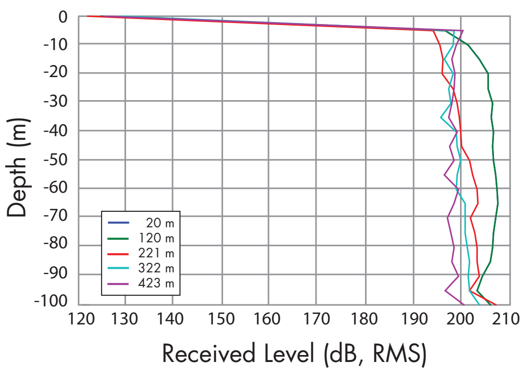


Figure 1.5.
Received levels vs. depth at different ranges. KRAKEN results. Summer 200 m depth.

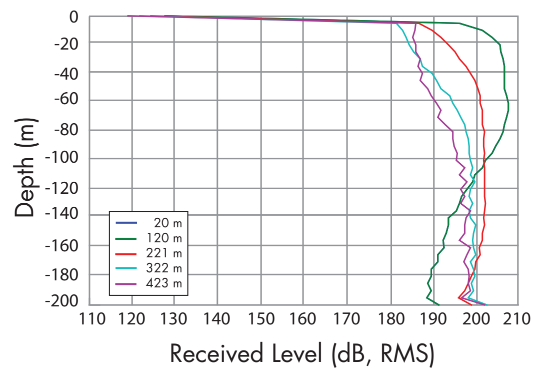


Figure 1.6.
Received levels vs. depth at different ranges. KRAKEN results. Summer 300 m depth.

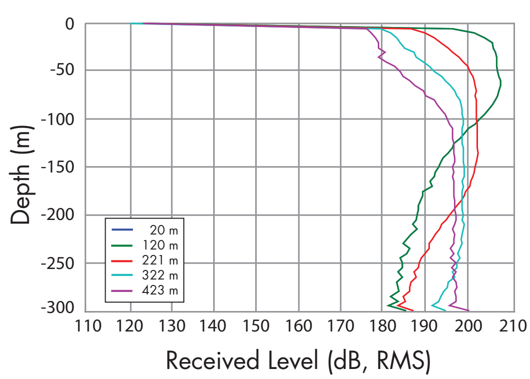


Figure 2.1.
Received levels vs. depth at different ranges.KRAKEN C results. Winter 100 m depth.

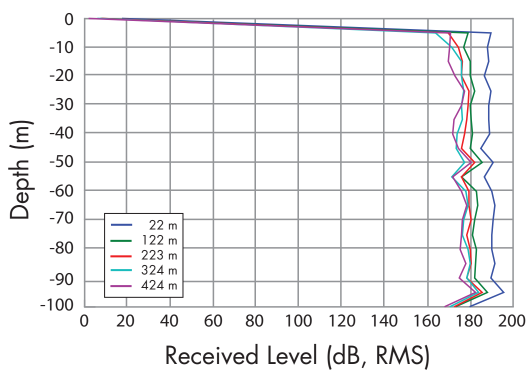


Figure 2.2.
Received levels vs. depth at different ranges. KRAKEN C results. Winter 200 m depth.

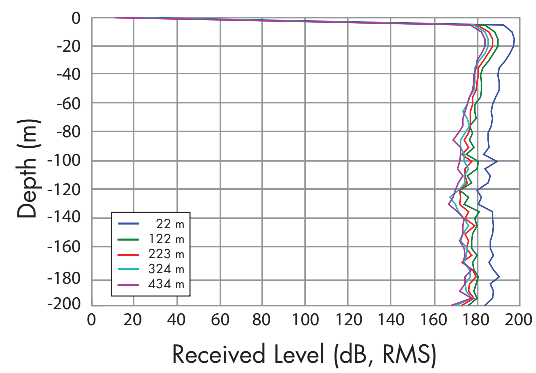


Figure 2.3.
Received levels vs. depth at different ranges.KRAKEN C results. Winter 300 m depth.

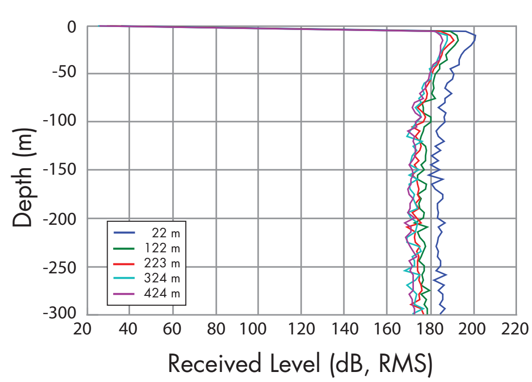


Figure 2.4.
Received levels vs. depth at different ranges.KRAKEN C results. Summer 100 m depth.

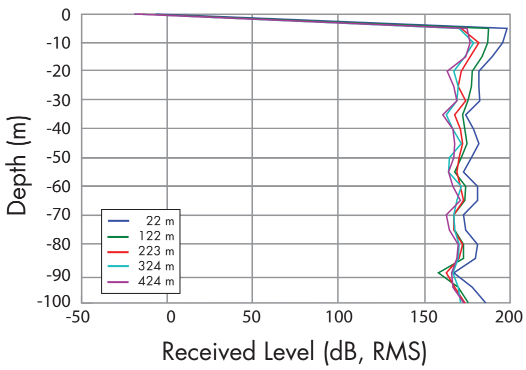


Figure 2.5.
Received levels vs. depth at different ranges. KRAKEN C results. Summer 200 m depth.

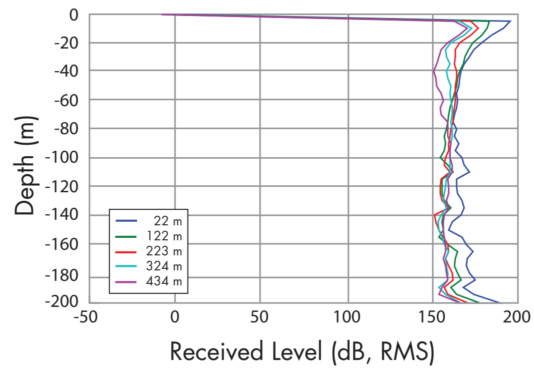
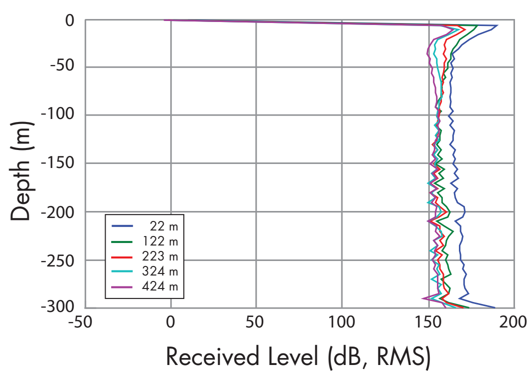


Figure 2.6.
Received levels vs. depth at different ranges. KRAKEN C results. Summer 300 m depth.



3. KRAKEN RUNS WITH NO SEDIMENT BOTTOM

Figure 3.1.
Received Levels (dB, RMS) Vs. Range at 5 different depths for a 250 dB (re 1 mPa at 1 m, p-p) source. KRAKEN results.
Winter, 100 m depth.

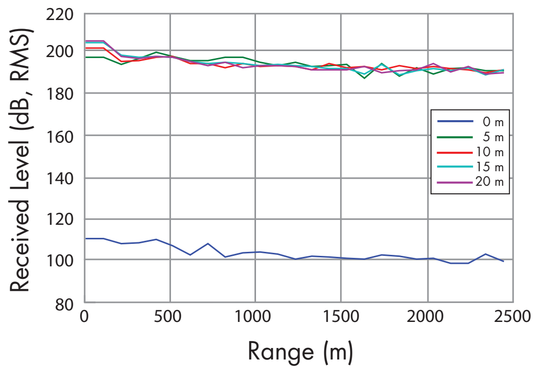


Figure 3.2.
Received Levels (dB, RMS) Vs. Range at 5 different depths for a 250 dB (re 1 mPa at 1 m, p-p) source. KRAKEN results.
Winter, 200 m depth.

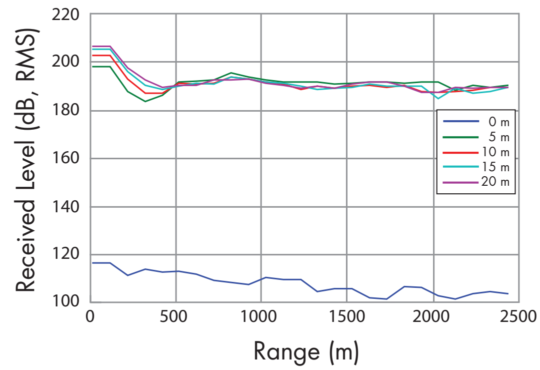


Figure 3.3.
Received Levels (dB, RMS) Vs. Range at 5 different depths for a 250 dB (re 1 mPa at 1 m, p-p) source. KRAKEN results.
Winter, 300 m depth.

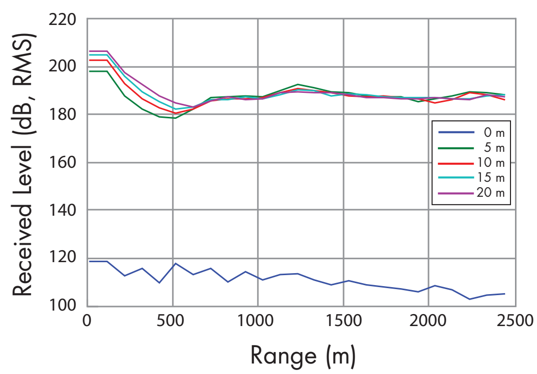


Figure 3.4.
Received Levels (dB, RMS) Vs. Range at 5 different depths for a 250 dB (re 1 mPa at 1 m, p-p) source. KRAKEN results. Summer, 100 m depth.

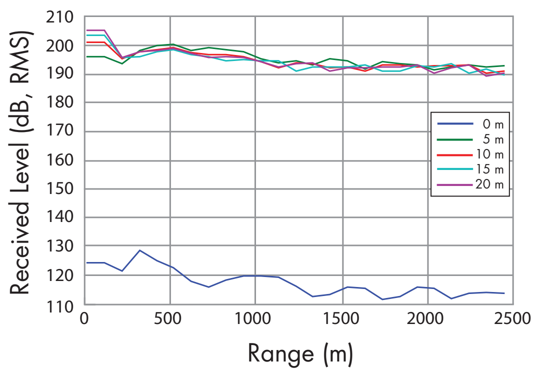


Figure 3.5.
Received Levels (dB, RMS) Vs. Range at 5 different depths for a 250 dB (re 1 mPa at 1 m, p-p) source. KRAKEN C results. Summer, 200 m depth.

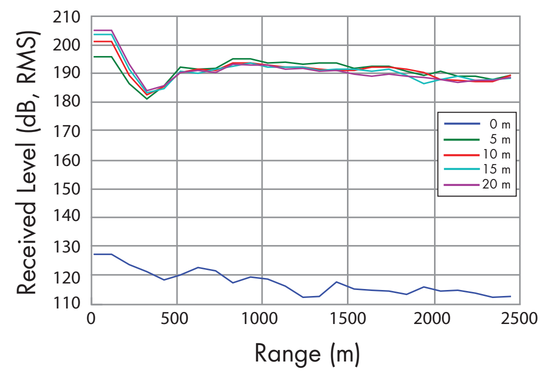
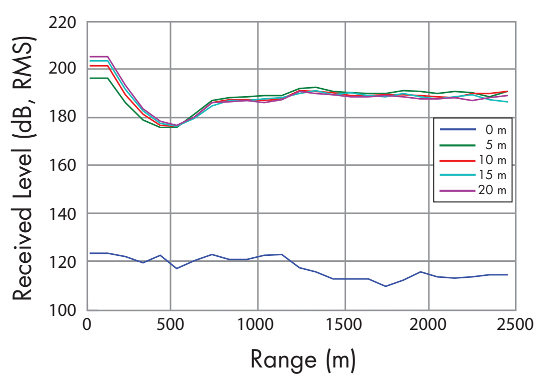


Figure 3.6.
Received Levels (dB, RMS) Vs. Range at 5 different depths for a 250 dB (re 1 mPa at 1 m, p-p) source. KRAKEN C results. Summer, 300 m depth.



4. KRAKEN C RUNS WITH SEDIMENT BOTTOM

Figure 4.1.
Received Levels (dB, RMS) Vs. Range at 5 different depths for a 250 dB (re 1 mPa at 1 m, p-p) source. KRAKEN C results. Winter, 100 m depth.

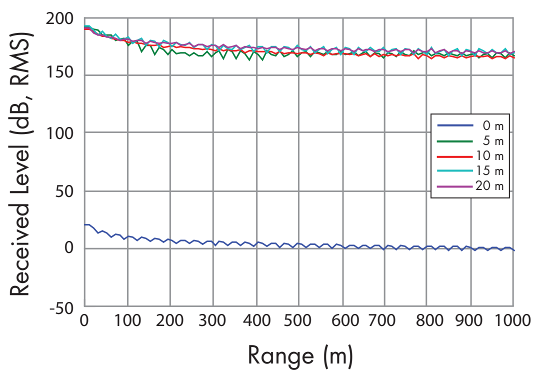


Figure 4.2.
Received Levels (dB, RMS) Vs. Range at 5 different depths for a 250 dB (re 1 mPa at 1 m, p-p) source. KRAKEN C results. Winter, 200 m depth.

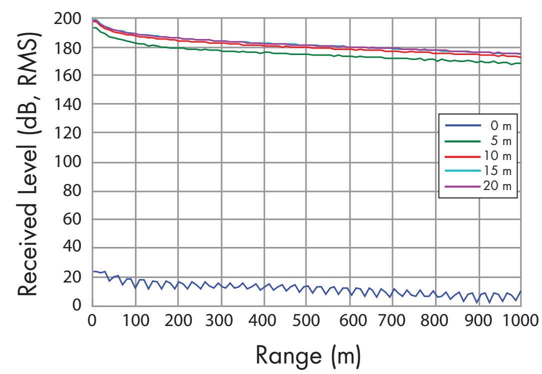


Figure 4.3.
Received Levels (dB, RMS) Vs. Range at 5 different depths for a 250 dB (re 1 mPa at 1 m, p-p) source. KRAKEN C results. Winter, 300 m depth.

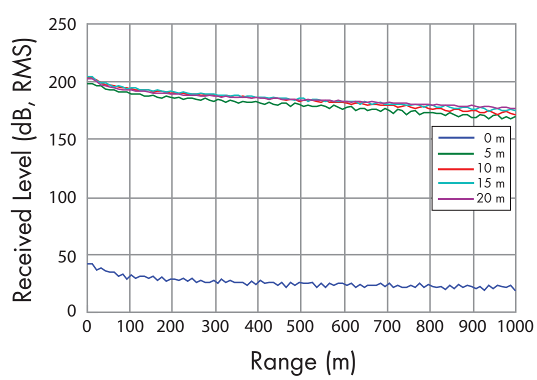


Figure 4.4.
Received Levels (dB, RMS) Vs. Range at 5 different depths for a 250 dB (re 1 mPa at 1 m, p-p) source. KRAKEN C results. Summer, 100 m depth.

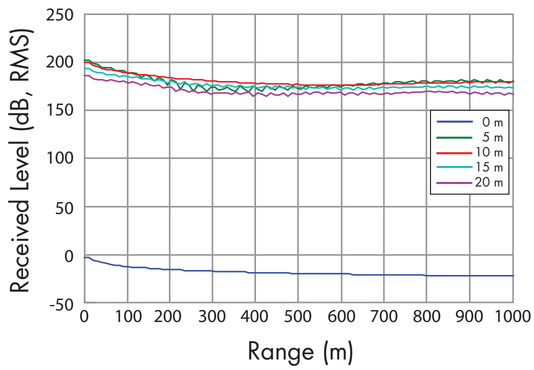


Figure 4.5.
Received Levels (dB, RMS) Vs. Range at 5 different depths for a 250 dB (re 1 mPa at 1 m, p-p) source. KRAKEN C results. Summer, 200 m depth.

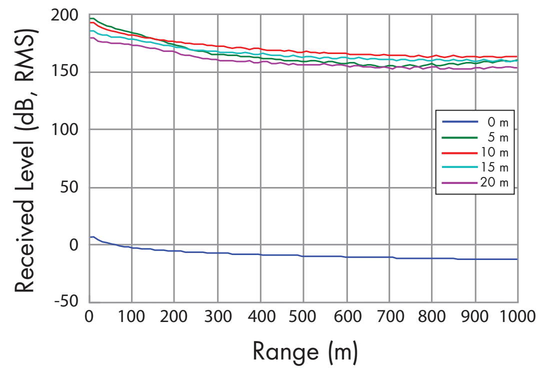


Figure 4.6.
Received Levels (dB, RMS) Vs. Range at 5 different depths for a 250 dB (re 1 mPa at 1 m, p-p) source. KRAKEN C results. Summer, 300 m depth.