14 Effect of Electromagnetic Fields on Marine Organisms

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14.1 Technical and Physical Background of Magnetic Fields

Artificial magnetic fields are unavoidable features of offshore wind farms in natural geomagnetic field environments. The movement of the wind over the blades makes them rotate and a connected shaft powers a generator to convert the energy into electricity. This electricity is transmitted by cables over long distances. Operating electric currents always produce magnetic fields, which are essentially dipolar in nature, having a north and a south magnetic pole.

The magnetic field lines of a straight current-carrying wire form concentric circles around the wire. The direction of the magnetic field is perpendicular to the wire and defined by the human right-hand rule, where the thumb of the right hand points in the direction of the conventional current and the fingers curl around the wire in the direction of the magnetic field. Direct electric currents (DC) produce static magnetic fields.

The impact of a magnetic field is described by the magnetic flux density (B). It is defined as the force acting per unit length on a wire carrying unit current (I). The magnetic flux density around a very long, straight wire can be calculated as:

$$B = \frac{\mu_0 \times I}{2\pi \times a}$$

B - magnetic flux density (SI-unit Tesla (T))
μ_0 - permeability of a vacuum $\mu_0=4\ \pi * 10^{-7}$ Hm^{-1}
I - current carried by the wire (SI-unit Ampere (A))
a - perpendicular distance from the wire to the point were the flux is being evaluated (m)

The magnetic flux density or magnetic intensity in the environment of a straight wire depends on the value of the electric current, in so far as the magnetic intensity increases with the electric current. In contrast, the magnetic intensity decreases with increasing distance from the wire.

There exists a great variety of feasible technical solutions to the problem of electric power transfer from offshore wind farms. Both variants, alternating current (AC) and direct current (DC) have been used. In addition to single, unipolar power cables systems, bipolar solutions also exist, in which two wires are arranged bipolar in one or two single submarine cables. Each of these variants will produce a different magnetic field. As in alternating current the magnitude and direction of the current varies cyclically, the magnetic field direction changes accordingly. In addition AC-induced magnetic fields lead to the development of electric fields, but technical designs of power cables are able to shield the environment from them. The magnetic intensity of two parallel wires results from the sum of their single fields, with the magnetic field intensity at a given point increasing if the currents are flowing in the same direction and decreasing if they flow in opposite directions.

As mentioned above, the magnetic field intensity of the environment of a single wire system depends on the electric current (I) and the distance (a) from the wire. Electric currents of 850 Ampere (A) and 1,600 A are characteristic of underwater sea cables. From these an artificial magnetic field of about 3.2 Millitesla (mT) is induced near a single wire at 1,600 A. The magnetic intensity decreases to 0.32 mT at a distance of 1 meter (m) and to 0.11 mT in a distance of 4 m. Even at this distance, the artificial magnetic field exceeds the natural geomagnetic field. Geomagnetic field values range from about 0.02 to 0.07 mT, with about 0.05 mT observed in the North and Baltic Seas areas.

14.2 Geomagnetic Field Detection in Marine Organisms

Evidence for orientation in relation to the geomagnetic field is rare in marine animals. Lohmann (1985) and Lohmann et al. (1995) found magnetic orientation of the western Atlantic spiny lobster (*Panulirus argus*). *Panulirus argus* undergoes an annual mass migration. Thousands of lobsters vacate shallow, inshore areas and crawl seaward in single-file, head-to-tail processions. Lines of lobsters within the same geographical area follow nearly identical compass bearings (Lohmann et al. 1995). This navigation based on a magnetic map sense, whereby the lobsters derive positional information from geomagnetic field (Boles and Lohmann 2003) using magnetic material concentrated in the cephalothorax, particularly in tissue associated with the fused thoracic ganglia (Lohmann 1984).

Sea turtles undertake a trans-oceanic migration in which they gradually circle the north Atlantic Ocean. They can distinguish between different earth magnetic field densities, and possess the minimal sensory abilities necessary to approximate their global position using a bicoordinate magnetic map (Lohmann and Lohmann 1996). This guidance system exists even in young loggerhead sea turtles (*Caretta caretta*), in which regional magnetic fields function as navigational markers and elicit changes in swimming direction at crucial geographic boundaries. Sea turtles are able to distinguish magnetic differences below 9 mT (Lohmann et al. 1999 and 2001).

Evidence for geomagnetic field orientation is also found in fish, molluscs and other crustaceans (Gill 2005). Juvenile salmon (*Oncorhynchus tschawytscha*), European silver (migratory) and yellow (stationary) eels (*Anguilla anguilla*) are able to respond to the earth's magnetic field (Karlsson 1985, Tesch et al. 1992). Lohmann and Willows (1987) found this phenomenon in the nudibranch mollusc (*Tritonia diomedea*), and chitons have radulae (tongues) that are covered by ferro-magnetic denticles which enables *Chaetopleura apiculata* to react to variation in ambient magnetic conditions (Ratner 1976). Sandhoppers (*Talitrus saltator*) also orient themselves towards magnetic fields, as has been revealed by experimental studies (Arendse and Kruyswijk 1981).

Barnwell and Brown (1964) found in the mud snail (*Nassarius obsoletus*) a response to a magnetic field only about nine times stronger than the local geomagnetic field.

14.3 Effects of Static Magnetic Field on Biological Systems

Magnetic fields interact directly with magnetically anisotropic or ferromagnetic materials, and with moving charges. They are almost unperturbed by biological tissues (Repacholi and Greenbaum 1999). Static magnetic fields may interact with living systems through magnetic induction (forces on moving ions in solution), magneto-mechnical effects (torques on molecules and ferromagnetic material) and electronic interactions (altering of energy levels and spin orientation of electrons, Repacholi and Greenbaum 1999). For instance, static magnetic fields can alter the early embryonic development in sea urchin embryos from *Lytechinus pictus* and *Strongylocentrotus purpuratus* by delaying the onset of mitosis (Levin and Ernst 1997).

14.4 Long-term Exposure of Marine Benthic Animals to Static Magnetic Fields

Several marine benthic animals could survive exposure to a static magnetic fields of 3.7 mT for several weeks (Table 1), and no differences occur in survival between experimental and control animals (Bochert and Zettler 2004). Mussels (*Mytilus edulis*) could live under this static magnetic field conditions for three month and the determination of gonad index and condition index during the reproductive period in spring revealed no significant differences from the control group (Bochert and Zettler 2004).

Table 1. Test organisms and test conditions for long-term magnetic field exposure experiment.

Test organism	Number of test animals	Number of control animals	Duration of experiment [days]
Young flounder (*Plathichthys flesus*) (Pisces)	18	6	28
Blue mussel (*Mytilus edulis*) (Bivalvia)	60	40	52
North Sea prawn (*Crangon crangon*) (Crustacea, Decapoda)	30	20	49
Glacial relict isopod (*Saduria entomon*) (Crustacea, Isopoda)	24	8	93
Round crab (*Rhithropanopeus harrisii*) (Crustacea, Decapoda)	30	10	57
Sphaeroma hookeri (Crustacea, Isopoda)	30	30	34

14.5 Short-term Exposure of Marine Benthic Animals to Static Magnetic Fields

Short-term reactions of the benthic crustaceans *Crangon crangon*, *Saduria entomon, Rhithropanopeus harrisii*, *Asterias rubens* (Echinodermata), *Nereis diversicolor* (Polychaeta) and young flounder *Platichthys flesus* (Pisces) to an artificial static magnetic field were tested in a laboratory study. Magnetic flux density (B) was approx. 2.7 mT. Test animals could decide to leave, to accumulate or to rest in the section of the experimental aquarium subjected to the magnetic field.

The test organisms *Crangon crangon*, *Nereis diversicolor* and *Platichthys flesus* were collected on 19 June 2002 and 18 July 2002 in the western Baltic Sea at an eulitoral station (54°01.562 N, 011°32.541 E) by using a fishing net of 0.5 mm mesh size, 0.5 m wide and in the case of *Nereis diversicolor* by using a fork. *Saduria entomon* was collected by dredging offshore east of Rügen Island (54°42.352 N, 014°20.215 E) on 28 October 2002. *Asterias rubens* was collected by dredging near shore west of Rostock (54°10.630 N, 011°44.549 E) on 15 December 2002. *Rhithropanopeus harrisii* was sampled by hand catching from docks of a small fishing harbour of Rügen (54°18.727 N, 013°40.922 E) on 29 August 2002.

After transport to the laboratory, animals were kept in plastic aquaria 145 x 240 x 150 mm filled with about 10 mm of natural sediment and ambient Baltic Sea water. Animals were fed twice a week with small pieces of fish or *Mytilus edulis*.

All studies were performed in a cooling room at 10°C, at a salinity of 10 psu and a light/dark cycle of 13.5 h/10.5 h.

Investigations were performed with two ring coils, each 300 mm in diameter, arranged parallel with a distance of 200 mm between them (ELWE GmbH, Germany). A direct current power source (DF 3010 10A) generated a magnetic field up to $B=2.8$ mT. The artificial magnetic flux density was considerably higher than the total geomagnetic field of approx. 49 µT at Rostock (54°10.756 N, 012°04.804 E), with horizontal intensity of about 18 µT and a vertical component of about 46 µT. The magnetic flux density was measured by using a Model Koshava 4-magnetometer (Wuntronic GmbH, Germany). The maximum magnetic flux density was generated at the coil planes; values decreased towards the middle between both coils. A mean magnetic intensity was calculated, and values between the two single coils ranged about ± 8 % around the mean. All measurements were performed at the axial centre of the coil system, where magnetic field (MF) is highly homogenous.

Aquaria 660 x 18.7 x 260 mm were used for the experiment. The aquaria could be divided into two sections equal in space by positioning a movable glass pane. The coil system was positioned on one side of the aquaria and the sediment-filled bottom was arranged centrally, where magnetic force is homogenous (Fig. 1).

The system generated an artificial horizontally directed magnetic field. At the beginning of the experiment, equal numbers of test animals were placed at ambient population densities in each section, and the experiment was started by removing the inserted glass pane after an exposure time of approx. 1.5 hours. At the end of the experiment after 22 hours, the sections were closed again and numbers of animals at each section were counted. Control samples were run at the same time in a separate aquarium without a coil system.

Statistical analysis was performed by the Wilcoxon test. A statistical level of P < 0.05 was considered significant.

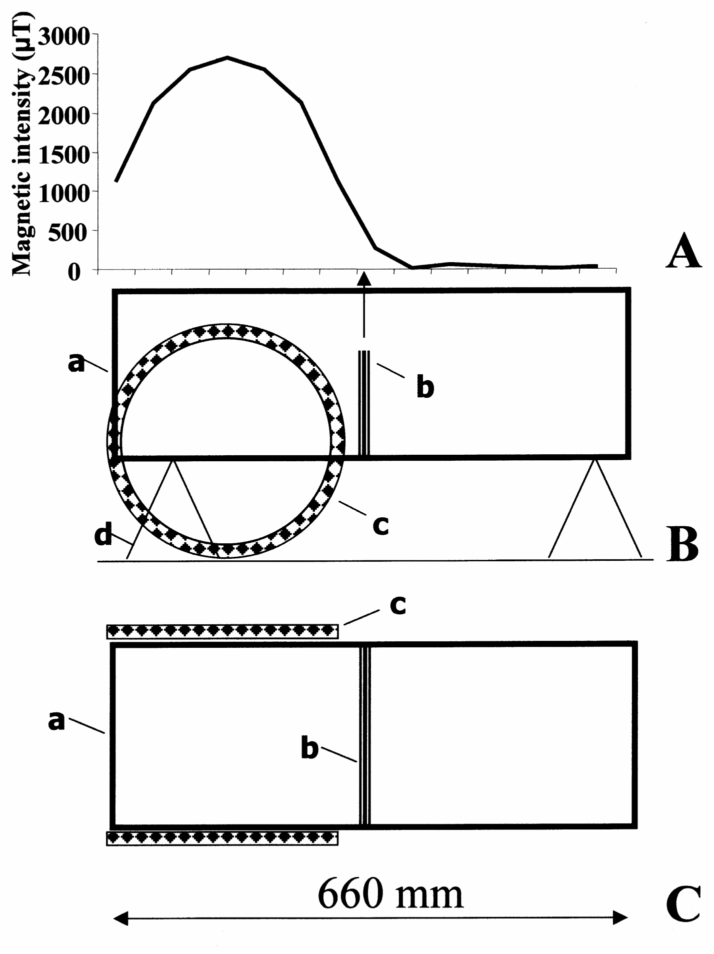

Fig. 1. Study design for magnetic field exposure. a - aquarium, b - movable glass pane, c - coil system, d - table-leg, A - magnetic intensity inside the aquaria along the long side of the aquaria, B - side view of aquaria and coil system, C - top view of aquaria and coil system

The distribution of *Crangon crangon* (six animals per section, 105 individuals per m²) in test aquaria was not different at the end of the experiment, and no significant difference to the control group was evident. The relationship between the sections affected and not affected by the magnetic field, repectively, was well-balanced, at 52 vs. 48 % (n=30). The control group spread was slightly unequal, at 57 and 43 % per section. The highest imbalance measured in both trials of the experiment was 10 to 2 animals, once per test series (Fig. 2).

Saduria entomon (three animals per section, 53 ind./m²) showed a tendency to leave the magnetic field area. Only one third (36 %) of individuals were found in this section at the end of the test series (n=20), whereas the control group was equally distributed. The high standard deviation resulted from a large scattering of single values; differences, at the 5 % level, were not statistically significant (Fig. 2).

Round crab *Rhithropanopeus harrisii* (six animals per section, 105 ind./m²) demonstrated uniform distributions, both for the test runs and for the controls. No differences were recognisable between the two trials. The highest mean values per trial were 54 and 61 % respectively (n=20) (Fig. 2).

The distribution of *Asterias rubens* (five animals per section, 90 ind./m²) remained nearly unchanged at the end of the test series (n=24). Mean values calculated per magnetic field trial peaked at 55 %, and reached 58 % for the control group (Fig. 2).

The tested polychaete *Nereis diversicolor* (six animals per section, 105 ind./m²) showed on average an unchanged distribution in relation to the initial allocation. The animals divided 52 % to 48 % in the test aquaria and 44 % to 56 % in the control group (Fig. 2).

Young flounders *Platichthys flesus*, 1 - 3 cm in length, (three animals per section, 53 ind./m²) showed no significant different distribution when tested with and without the magnetic field. In the magnetic field section, 59 % of the animals in mean were found, whereas without the artificial magnetic field, the mean was 53 % (Fig. 2).

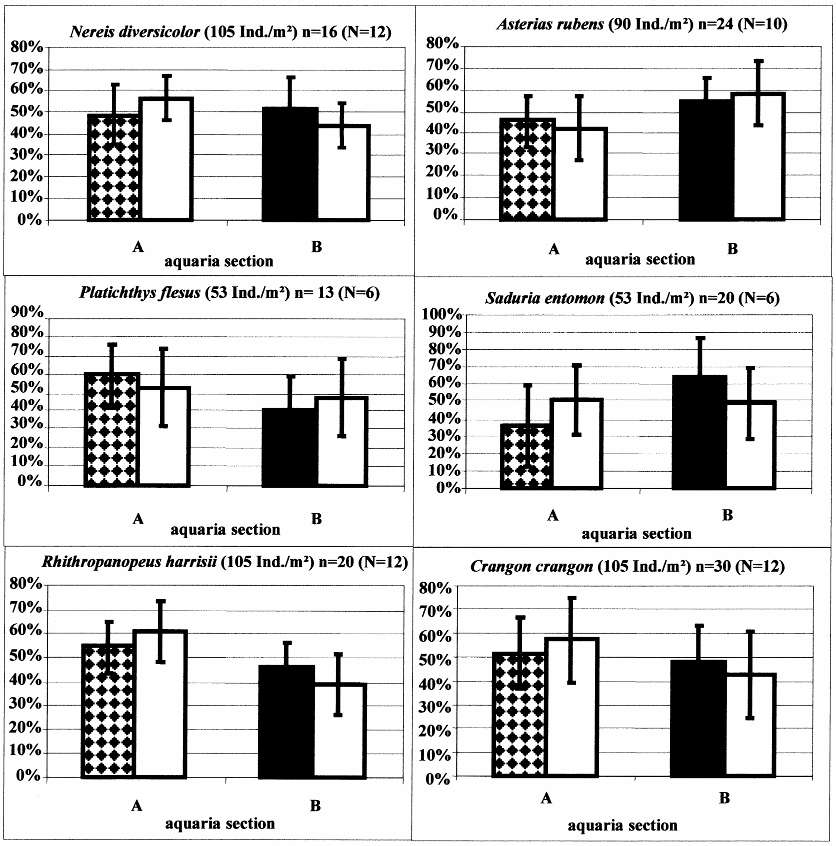

Fig. 2. Short term reaction of *Nereis diversicolor*, *Asterias rubens*, *Crangon crangon*, *Saduria entomon*, *Platichthys flesus* and *Rhithropanopeus harrisii* to a magnetic field. Mean percentage (± standard deviation) distribution of n experimental runs and N number of individuals (number of individuals per m^2 in brackets) in two aquarium sections. Dotted bar - high magnetic intensity, black bar - low magnetic intensity, white bar - control

14.6 Oxygen Consumption of *Crangon crangon* and *Palaemon squilla*

The oxygen consumption of two North Sea prawns *Crangon crangon* and one *Palaemon squilla* prawn were observed in a closed flow-through system under similar external conditions. Animals were kept three times for three hours in a static magnetic field, in a frequent (50 Hertz) magnetic field of B = 3.2 mT and without a magnetic field.

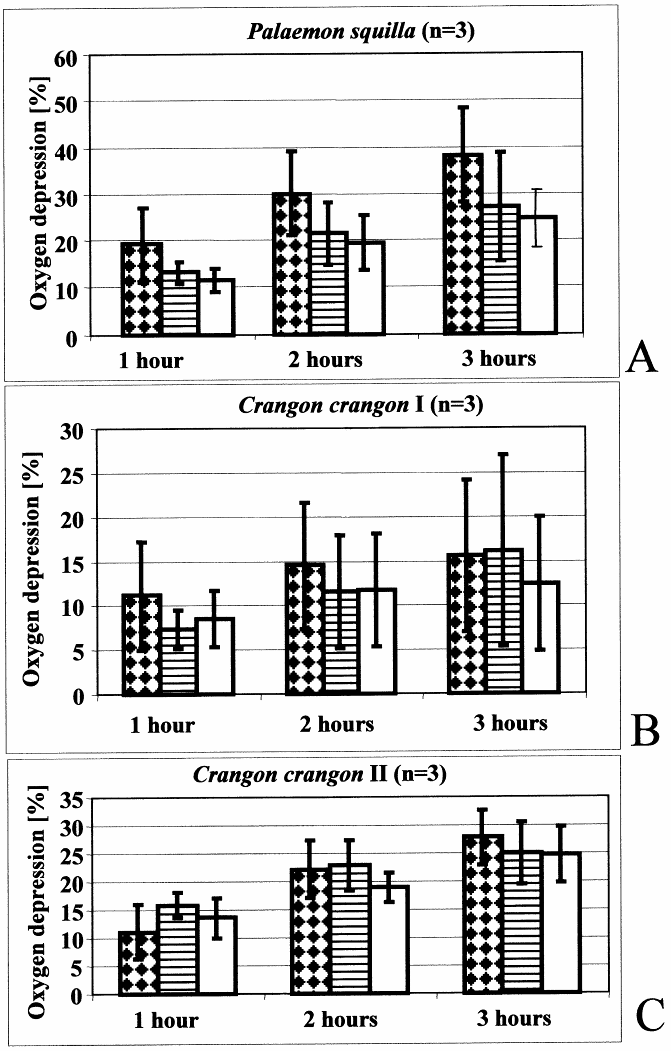

Fig. 3. Mean oxygen consumption (percentage depression) (± standard deviation, n=3) of three decapod crustaceans *Palaemon squilla* (A) and *Crangon crangon* (B, C) during exposure to a B = 3.2 mT static (DC) (dotted bar) and frequent (AC) (lined bar) magnetic field and during control conditions (white bar) after 1 hour and cumulatively after 2 and 3 hours

Oxygen consumption of one *Palaemon squilla* and two *Crangon crangon* showed no significant differences between exposures to static (DC), frequent (AC) magnetic fields, and under control conditions. Cumulated mean oxygen consumption increased in *Palaemon squilla* from 11 - 19 % in the first hour to 24 - 47 % after three hours (Fig. 3A). Mean oxygen consumption was higher during static magnetic field exposure, but differences were not significant. Mean oxygen consumption in two *Crangon crangon* revealed values of 12 - 27 % after three hours and no differences to control were observed (Fig. 3B, C).

14.7 Conclusions

All points on the earth's surface are characterised by the presence of a static geomagnetic field. The amount of total field intensity, which consists of a horizontal and a vertical component, depends on locality, and varies from 20 to 75 µT. However, these low natural values are enough to stimulate reactions in some marine animals of different groups, such as sea turtles (Lohmann and Lohmann 1996a; Lohmann et al. 1999, 2001), fish (Karlsson 1985; Taylor 1986; Tesch et al. 1992), molluscs (Barnwell and Brown 1964; Ratner 1976; Lohmann and Willows 1987) and crustaceans (Arendse and Kruyswijk 1981; Lohmann 1985). Elasmobranch fish are able to sense magnetic fields by their ampullae of Lorenzini (Kalmijn 1982).

In addition to the geomagnetic fields, marine benthic fauna could be subjected to artificial magnetic fields (Gill 2005), which, at a current of I=1,600 A, could produce a magnetic flux density of B=3.2 mT at a distance of 0.1 m, 1.0 mT at a distance of 0.3 m, and even at a distance of 6 m it is in the range of natural geomagnetic field, at about 50 µT. Studies of possible effects of artificial static magnetic field have been carried out in various systematic groups and under various experimental conditions. It has been shown that externally applied magnetic fields could interact with biological systems to produce detectable changes. Often, these findings are very slight differences to control groups, and no clear-cut effects of steady magnetic fields are yet available. In the hydroid *Clava multicornis,* reproduction was faster at a magnetic intensity of 10 and 20 mT than in control and at 40 mT (Karlsen and Aristharkhov 1985). In *Mytilus edulis,* magnetic field action of 5.8, 8 and 80 mT leads to a 20 % decrease in hydration and 15 % decrease in amine nitrogen values (Aristharkhov et al. 1988). Guppies (*Lebistes reticulates*) survived a continuous magnetic treatment of 50 mT for 200 days. In the first generation, but the second generation had an average reduction of spawning rate of 50 % and in the third generation, reproduction was completely inhibited as long as the fish remained within the magnetic field (Brewer 1979).

Our results indicate that all the animals we tested did not react when exposed to an artificial magnetic field. Static magnetic fields of submarine cables seem thus to have no clear influence on orientation, movement and physiology of the tested benthic animals.

Further studies which focus on a long-term approach and different conditions (AC/DC, uni- and bi-polar cables, other species, individual to cellular level etc.) are necessary to confirm fully the harmlessness of power transmission on the marine environments.

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