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Exponent®

Submarine Cable DC Magnetic Field in Lake Champlain and Marine Assessment

Submarine Cable DC Magnetic Field in Lake Champlain and Marine Assessment

Prepared for

Champlain VT, LLC d/b/a TDI New England

Prepared by

Exponent
17000 Science Drive
Suite 200
Bowie, MD 20715

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Acronyms and Abbreviations

µT	Microtesla
µV	Microvolts
µV/cm	Microvolts per centimeter
µV/m	Microvolts per meter
A	Amperes
AC	Alternating current
cm/s	Centimeters per second
DC	Direct current
HDD	Horizontal directional drilling
HVDC	High voltage direct current
ICD	Implantable cardioverter defibrillator
IGRF	International Geomagnetic Reference Field
ICNIRP	International Commission on Non-Ionizing Radiation Protection
kV	Kilovolt
mG	Milligauss
mm	Millimeter
mT	Millitesla
MW	Megawatt
nT	Nanotesla
nV/cm	NanoVolts per centimeter
NECPL or Project	New England Clean Power Link project
TDI-NE	Champlain VT, LLC, d/b/a TDI-New England

Executive Summary

Champlain VT, LLC, d/b/a TDI-New England is proposing the New England Clean Power Link project (NECPL or Project). The NECPL is a high voltage direct current electric transmission line that will provide electricity generated by renewable energy sources in Canada to the New England electric grid. The line will run from the Canadian border at Alburgh, Vermont, along underwater and underground routes to Ludlow, Vermont.

The transmission line will be comprised of two approximately five-inch, solid dielectric cables—one positively charged and the other negatively charged—and contain no fluids or gases. The nominal operating voltage of the cables will be approximately ±320 kilovolts, and the system will be capable of delivering 1,000 megawatts of electricity.

This report summarizes Exponent's calculations of direct current (DC) magnetic fields associated with the operation of the cables in Lake Champlain in two modeling scenarios that represent the range of magnetic field level changes associated with the proposed Project. These calculations take into account the joint contributions from the cables and the earth to the total DC magnetic field that would be measured around the cables. The calculated magnetic fields are presented as changes from the earth's ambient geomagnetic field level as well as in terms of calculated changes to compass bearings.

The effect of the NECPL cables on the ambient geomagnetic field will be limited largely to the area immediately surrounding the NECPL cables. The calculated DC magnetic field deviations and compass deflections fall off rapidly with distance from the NECPL cables. Calculated magnetic field deviations at 10 feet from the cables are less than 10% of the ambient geomagnetic field level. Only slightly further away, at 25 feet from the cables, the magnetic field deviation is approximately 1% of the ambient geomagnetic field level. The highest calculated magnetic field level anywhere along the submarine portion of the route (calculated at 1 foot above the lakebed, directly over the NECPL cables) is approximately 0.1% of the general public exposure limit (4,000,000 milligauss [mG]) recommended by the International Commission for Non-Ionizing Radiation Protection, and decreases substantially at distances

further from the cable. The highest calculated magnetic field is also well below applicable medical device standards for exposure to DC magnetic fields (10,000 mG).

Boaters who may be using traditional compasses that rely on the earth's magnetic field may detect a small effect on compass readings above the buried cables in shallow water that will diminish quickly with distance. In water depths of just 10 feet, the maximum compass deviation would be 8 degrees directly over the cable and would decrease to 1.3 degrees at a distance of 10 feet or more from the cable centerline. The compass deviation also decreases as the depth of water over the cable increases, and will be less than 2.9 degrees directly over the cable at depths greater than 19 feet. Where the cables are not buried at depths > 150 feet, the deviation at the lake surface would be less than one degree. Compass readings and locations obtained from global positioning system receivers would not be affected by the NECPL cables.

A review of neurobiological research to date did not indicate that the change in the geomagnetic field around the cable would cause adverse impacts on resident populations of aquatic species. The electric field produced by voltage on the cables will be shielded from the aquatic environment by metallic sheathing on the cables, but weak electric fields around the cables are induced by the movement of water borne charges in the magnetic field. Changes in the DC magnetic field and associated induced electric field in moving water currents are likely to be detected by some species with specialized sensory receptors for static magnetic fields and low frequency electric fields (e.g., sturgeon), but the very limited area around the cables where these fields would be increased is tiny relative to the area of Lake Champlain through which the cables will traverse. This suggests that the probability of resident aquatic species encountering areas with significantly altered magnetic fields associated with the buried cable is very low.

Introduction

Champlain VT, LLC, d/b/a TDI-New England (TDI-NE) is proposing the New England Clean Power Link project (NECPL or Project). The NECPL is a high voltage direct current (HVDC) electric transmission line that will provide electricity generated by renewable energy sources in Canada to the New England electric grid. The line will run from the Canadian border at Alburgh, Vermont, along underwater and underground routes to Ludlow, Vermont.

The transmission line will be comprised of two approximately five-inch diameter cables—one positively charged and the other negatively charged—and will be solid-state dielectric and thus contain no fluids or gases. The nominal operating voltage of the line will be ±320 kilovolts (kV), and the system will be capable of delivering 1,000 megawatts (MW) of electricity.

The proposed underwater portion of the transmission line, approximately 98 miles in length, will be buried to a target depth of 3 to 4 feet in the bed of Lake Champlain except at water depths of greater than 150 feet, where the cables will be placed on the lake bottom and self-burial of the cables in sediment will occur. In a few areas where there are obstacles to burial (e.g., existing infrastructure or bedrock), the cable will lie on the lake bottom and protective coverings may be installed.

To describe the magnetic field exposures associated with the proposed project, Exponent calculated DC magnetic flux densities (referred to hereafter to as magnetic fields) associated with the operation of the underwater cables in Lake Champlain in two modeling scenarios that represent the range of expected magnetic field changes in Lake Champlain. These calculations take into account the joint contributions from the cables and the earth to the total DC magnetic field that would be measured around the cables. In two very short (3,662 foot) sections, the NECPL cables will enter and exit the lake to land via horizontal directional drilling (HDD). Since the change in the geomagnetic field from this HDD configuration will be similar to other cases described below, the magnetic field from this section was not modeled separately. Although the electric field from the cables is wholly shielded from the environment by grounded metallic sheaths around each cable, water flow in a static magnetic field (whether from the earth or the NECPL cables) induces a very weak static electric field, which is addressed separately.

The effects of potential human exposure to magnetic and induced electric fields are addressed by comparison to established standards. Exposures to the aquatic environment are not covered by these standards, and so review of the relevant scientific literature was performed to provide a context for evaluation of potential impacts.

Magnetic Field Standards

Neither the State of Vermont nor the federal government has a standard for static magnetic fields from transmission lines.[1] For static magnetic fields, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) has a recommended a general public exposure limit of 4,000,000 milligauss (mG) (ICNIRP, 2009).[2] This exposure limit encompasses large safety factors to preclude any established biological effect. For persons with implantable medical devices the limit for exposure to static magnetic fields is determined by other standards such as the Association for the Advancement of Medical Instrumentation's standard PC69:2007, which specifies that no changes in the function of the pacemaker or the implantable cardioverter defibrillator (ICD) should occur up to 1 millitesla (mT) (i.e., 10,000 mG). After exposures to static magnetic fields up to 500,000 mG (50 millitesla), the standard requires that the functions of a pacemaker or ICD not be affected after discontinuation of the exposure.[3]

[1] There are differences between static fields and alternating current fields (e.g., the 60-Hertz fields associated with our power system) in the way they interact with objects in the environment, so different standards have been developed for each of these frequencies. This accounts for the ICNIRP standard for static magnetic fields being set at a far higher level than its 2010 standard for 60-Hertz alternating current magnetic fields (2,000 mG).

[2] ICNIRP also recognizes that persons with implantable medical devices (such as pacemakers and intracardiac defibrillators) should consult other standards such as AAMI PC69:2007 and IEC 60601-2 which recommend such persons not be exposed to static magnetic fields in excess of 5,000 mG.

[3] The AAMI PC69:2007 standard has been superseded by 14117:2012, but this new standard is not yet recognized as a consensus standard by the Food and Drug Administration. There is no difference in static magnetic field values between PC69:2007 and 14117:2012.

Methods

Magnetic Field

The DC magnetic field from the submarine cables was calculated by the application of the Biot-Savart Law to the specific cable configurations for NECPL that were provided to Exponent by TDI-NE. The Biot-Savart Law is derived from fundamental laws of physics and is used to compute the magnetic field produced by the flow of electric current in a conductor. Application of the Biot-Savart Law is particularly appropriate for long straight conductors such as the NECPL cables.[4]

Calculations were performed for two primary modeling scenarios that represent the range of installation depths in the lake (i.e., 3 feet below the lakebed and laid on the lakebed). Case T represents the typical configuration of the NECPL cable, trenched to a minimum of 3 feet beneath the lakebed with the two cables strapped together and oriented vertically such that the two cables are atop one another (i.e., Trench Configuration – Case T). According to the Applicant, this configuration would be installed in 54% of the route. Case B describes the scenario expected along 2% of the route where the two cables are laid horizontally adjacent to one another on the bottom of the lakebed and no self-burial occurs due to the presence of bedrock or existing infrastructure (i.e., Bedrock Configuration – Case B). Where the cables are laid on the lakebed at depths >150 feet, analyses indicated that the weight of the cables will cause the cables to sink about 1 foot below the surface of the lakebed and so the results for this case will fall between those of the two cases modeled (i.e., Self-Burial Configuration – Case S). The two modeling cases (Case T and Case B) are summarized below in Table 1.

[4] $B = \mu_0 H = \mu_0\ I/2\pi r$, where B is the magnetic flux density, $\mu_{0\ \mathrm{Is}}$ the magnetic permeability of a vacuum, I = current, and r = the distance from each cable conductor.

Table 1. Cable conditions in Case T and Case B

Conditions	Configuration: Cables Buried in Trench (Case T)	Configuration: Cables Resting on Bedrock (Case B)
Proximity of Cables	Touching	Touching
Cable Orientation	Cables Vertical	Cables Horizontal
Burial Depth (to top of cable)	3 feet	N/A (on lakebed)
Direction of Electrical Current Flow	North/South	North/South
Cable Diameter	135 mm	135 mm

Note: These assumptions originated from TDI-NE based on their consultations with marine cable installers and manufacturers.

The loading of each of the two ±320 kV DC cables was assumed to be 1,650 amperes (A), a conservative assumption for modeling 1,000 MW of delivered power. Magnetic fields were calculated for two arrangements of DC cables with a (+) and (–) polarity, the configurations of which are summarized in Table 1.

The (+) and (-) cables were assumed to be strapped together and touching, resulting in a separation of 135 millimeters (mm) [5.3 inches] between the centers of horizontally or vertically adjacent cables in both cases, and the burial depth was measured between the lakebed and cable centers. For each case, the magnetic field, expressed as magnetic flux density in units of mG, was calculated along transects perpendicular to the route of the cables at heights of 1, 10, and 19 feet above the lakebed to describe a range of field levels likely to be encountered by aquatic life and boaters.

In order to understand the change in the magnetic field, the geomagnetic field at the center of Lake Champlain was obtained from the International Geomagnetic Reference Field (IGRF) Model.[5] The geomagnetic field at 44.200868°N latitude and 73.373461°W latitude (approximately at the center of Lake Champlain, northwest of Vergennes, Vermont) was used in all calculations, corresponding to the geomagnetic components shown in Table 2. At this location, the geomagnetic field has a -14.35 degree declination (westward) and 69.29 degree inclination (downward).

[5] National Geophysical Data Center. http://www.ngdc.noaa.gov/geomag/data.shtml.

Table 2. Total geomagnetic field

Component	Geomagnetic field (in nanotesla [nT] and mG)		
Northern component	18345.4 nT	=	183.45 mG
Eastern component	-4694.3 nT	=	-4.69 mG
Downward component	50084.0 nT	=	500.84 mG
Total geomagnetic field			535.44 mG

Along the Project route, the geomagnetic field does not vary sufficiently to affect the reported magnetic field values and compass deflections by more than 0.5%.

The magnetic field from the earth and from the NECPL cables are both static (i.e., not time varying to any appreciable extent) and their vectors (with a strength and a direction) will determine the total magnetic field (geomagnetic field + NECPL cables). This total magnetic field will either increase or decrease at any particular location based upon the orientation of the cable and the polarity of its operation. In order to show the total magnetic field and the local change of the earth's geomagnetic field due to the NECPL, the magnetic field vectors from the cable along x, y, and z axes were combined with the parallel vectors of the earth's main geomagnetic field as determined by the latest IGRF Model (i.e., IGRF 11)[6] for specified latitude and longitude coordinates to obtain the total resultant magnetic field.

Compass Deflection

The horizontal component of the earth's dipole magnetic field causes a compass needle to orient in a north-south direction. Compass needle alignments in Lake Champlain around the cables were calculated based upon calculations of the combined horizontal magnetic field vectors of the earth and the cables.

Induced Electric Field

The movement of electric charges in the ambient environmental magnetic field of the earth or as altered by the presence of a DC submarine cable gives rise to an induced electric field, which

[6] National Geophysical Data Center. http://www.ngdc.noaa.gov/geomag/data.shtml.

will depend on the speed and direction the water (or a fish) passes over the cable. As discussed a report prepared for the Bureau of Ocean Energy Management, Regulation, and Enforcement (Normandeau et al., 2011), the Lorenz force is responsible for electric fields up to about 0.75 microvolts per meter (µV/m) measured in the ocean and other water bodies. Far higher electric fields up to 150 µV/m have been measured over certain bottom sediments and attributed to electrochemical effects (Pals and Schoenhage, 1979). To the extent that a submarine cable increases the DC magnetic field above that of the ambient geomagnetic field in the water column over the cable, the induced electric field in water will be increased as well.

The induced electric field is calculated by applying Lorentz's law, as outlined in Normandeau, et al. (2011), in which the electric field magnitude *E* is expressed as

$$E = \frac{F}{q}$$

and

$$F = qvB\sin\theta$$

where

F = magnitude of the force vector **F**,
q = the electric charge,
v = magnitude of the velocity vector **v**,
B = magnitude of the magnetic flux density vector **B**, and
sin θ = sine of the angle θ between the directions of the vectors **v** and **B**.

In the following analysis, the speed of the water or a fish (in centimeters per second) is substituted for the magnitude of the velocity vector **v**.

Results

Magnetic Field Deviations

Most of the route in Lake Champlain is described by the two cables modeled in a north-south direction. In Case T, when the top cable carries the northward current,[7] the change in the magnetic field is shown in Figure 1. Figure 1 depicts the magnetic field (geomagnetic field + NECPL cable field) calculated for a 3-foot cable burial depth and vertically adjacent cables, along transects 1, 10, and 19 feet above the lakebed. The calculated magnetic field for cables laid horizontally adjacent to one another on the lakebed (0 foot burial depth) and with the eastern cable carrying northward current is depicted in Figure 2. Calculations for the scenario where the direction of current flow in the two cables is reversed have also been performed, showing similar results with slightly smaller deviations. The results of these two other scenarios are included in Appendix A, Table A-1.

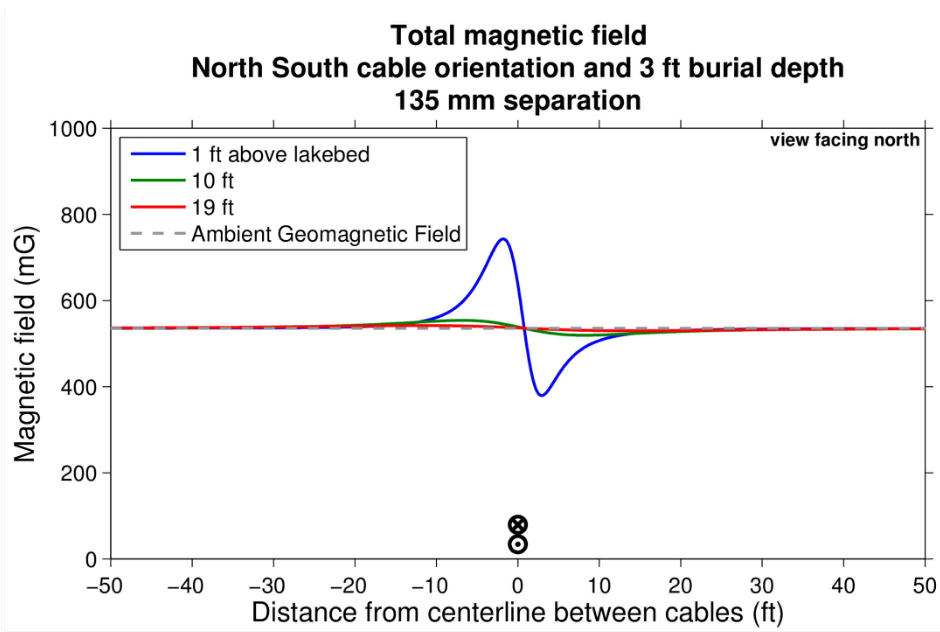

Figure 1. Case T. Magnetic field profiles (mG) above north-south oriented cables buried 3 feet, cables separated by 135 mm, and northward current in the top cable.

7 The two cables have opposite polarity (i.e., each cable carries electricity that flows in opposing directions). TDI-NE has not yet determined which cable (“top” cable or “bottom” cable) will carry electricity flowing north and which will flow south, so both cases were modeled. Results for both cases are qualitatively similar.

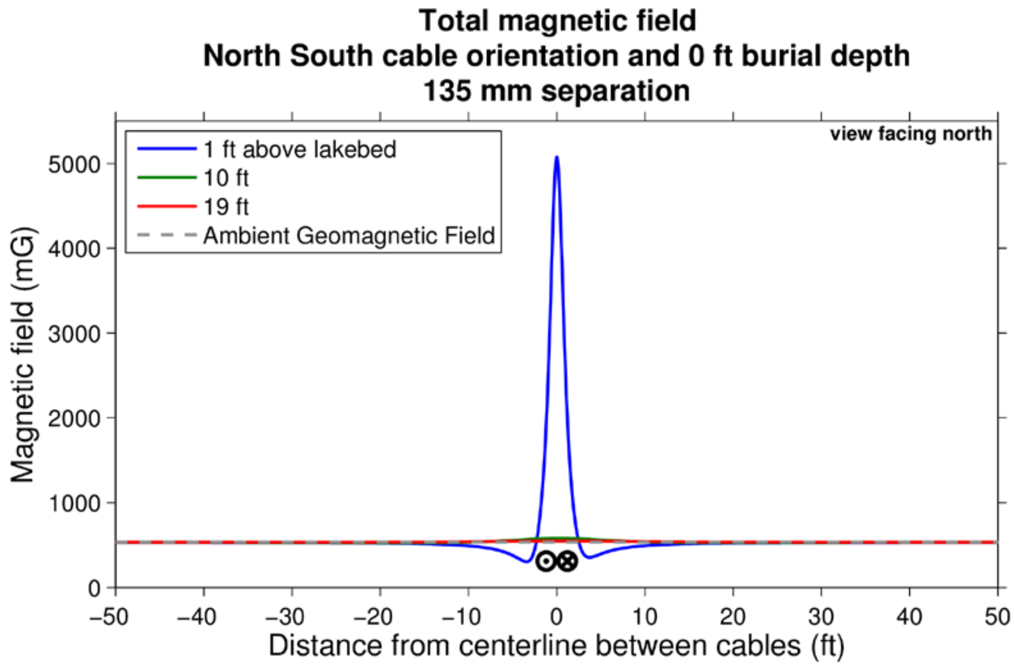

Figure 2. Case B. Magnetic field profiles (mG) above north-south oriented cables on the lakebed, cables separated by 135 mm, and northward current in the eastern cable.

Note that the y-axis scale is different than that in Figure 1.

Tabulated magnetic fields corresponding to Figures 1 and 2 are summarized in Table 3. The magnetic field levels are tabulated as deviations from a 535 mG geomagnetic field magnitude.

Table 3. Magnetic field magnitude deviation (mG) from 535.44 mG geomagnetic field, above lakebed and for distances from centerline of bipolar DC circuit with north-south orientation of cables

Cable burial depth and phasing	Height above lakebed (feet)	Distance from circuit centerline							
		-50 feet	-25 feet	-10 feet	Max + deviation	Max - deviation	+10 feet	+25 feet	+50 feet
Case T									
3 feet	1	0.1	1.6	25.0	207.5	-156.2	-28.4	-2.8	-0.4
(northward current	10	0.7	4.3	16.6	18.4	-16.2	-15.6	-4.9	-1.0
on top)	19	1.0	4.0	6.3	6.4	-5.7	-5.3	-4.1	-1.2
Case B									
0 feet	1	-1.8	-7.2	-44.1	4539.7	-232.6	-42.3	-7.1	-1.8
(northward current	10	-1.7	-4.9	-1.6	45.2	-6.5	2.6	-4.1	-1.5
east side)	19	-1.3	-1.6	4.8	12.5	-1.8	6.3	-0.8	-1.1

Compass Deflection

Figure 3 depicts the calculated compass deflection along transects 1, 10, and 19 feet above the lakebed for the Case T configuration (3-foot cable burial depth and cables vertically adjacent) when the top cable carries the northward current. Figure 4 presents the compass deviations along transects 1, 10, and 19 feet above the lakebed for the Case B configuration where the cables are horizontally adjacent on the lakebed and the eastern cable carries the northward current. Compass deflections are presented as offsets from the 14.35 degree west geomagnetic declination (difference from magnetic north relative to geographic north) along the Project route. Positive values in the compass deflection correspond to an eastward declination.

Tabulated compass deflections corresponding to the results presented in Figures 3 and 4 as well as compass deviations for the additional phasing cases where the eastern cable carries the southbound current are summarized in Table 4. Calculations for the scenario where the direction of current flow in the two cables is reversed have also been performed, showing similar deviations. The results of these two other scenarios are included in Appendix A, Table A-2.

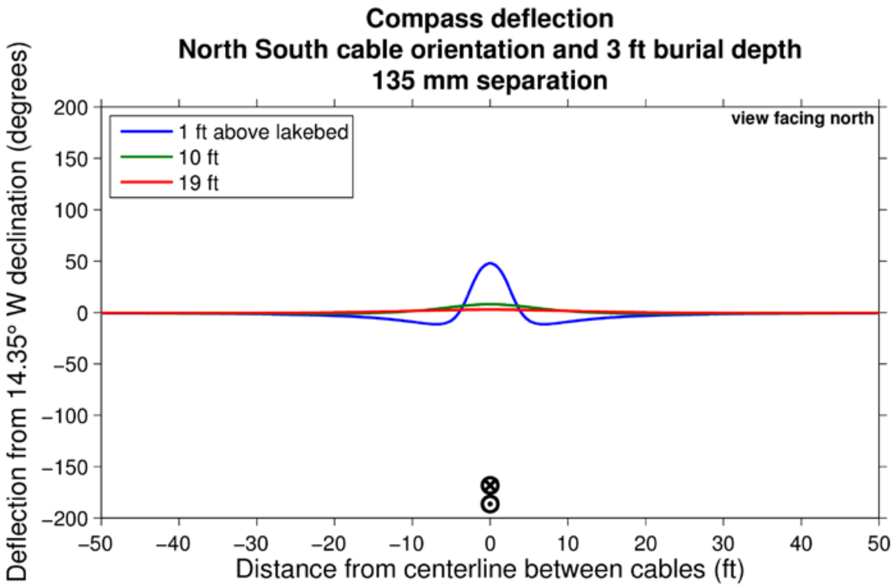

Figure 3. Compass deflection (degrees) from 14.35 degree W declination above north-south-oriented cables buried 3 feet, cables separated by 135 mm, and northward current in the top cable.

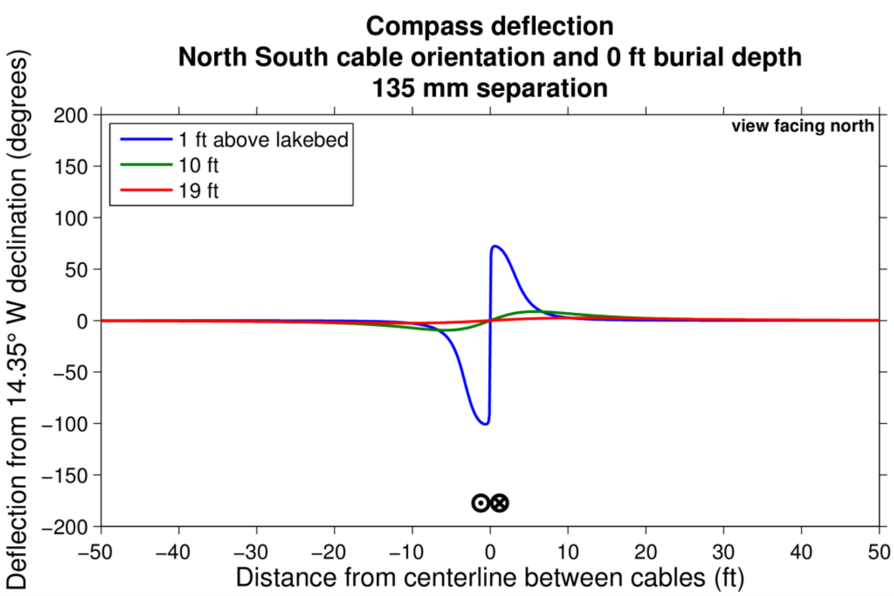

Figure 4. Compass deflection (degrees) from 14.35 degree W declination above north-south oriented cables on the lakebed, cables separated by 135 mm, and northward current in the eastern cable.

Table 4. Compass deflection (degrees) from 14.35 degree W declination above lakebed and distances from centerline of bipolar DC circuit with north-south orientation of cables

		Distance from circuit centerline							
Cable burial depth and phasing	**Height above lakebed (feet)**	**-50 feet**	**-25 feet**	**-10 feet**	**Max + deflection**	**Max - deflection**	**+10 feet**	**+25 feet**	**+50 feet**
Case T									
3 feet (northward current on top)	1	-0.6	-2.1	-9.1	47.8	-11.4	-9.1	-2.1	-0.6
	10	-0.5	-1.0	1.3	8.0	-1.0	1.3	-1.0	-0.5
	19	-0.3	-0.2	1.6	2.9	-0.4	1.6	-0.2	-0.3
Case B									
0 feet (northward current east side)	1	<0.1	-0.2	-2.8	72.2	-100.8	2.7	0.2	<0.1
	10	-0.2	-1.3	-7.2	8.7	-9.4	6.8	1.3	0.2
	19	-0.3	-1.4	-2.5	2.5	-2.6	2.5	1.4	0.3

Electric Field Induction

At a high typical water velocity of 4.8 centimeters per second (cm/s) typical of Lake Champlain (Manley et al., 1999), the induced electric field from the geomagnetic field alone will be very small, approximately 2.6 μV/m.

Where the presence of the NECPL cables affects the ambient geomagnetic field, the induced electric field will be affected as well. At average water velocity of 4.8 cm/s typical of high flow in the summer in Lake Champlain (flows in winter about 50% lower) (Manley et al., 1999), the induced electric field is approximately 3.7 μV/m directly over the trench-buried cables (Case T), falling below 2.6 μV/m at a distance of 10 feet away from the cables. In Case B, the induced electric field will be approximately 23.5 μV/m at a height of 1 foot above the lakebed, directly over the cables. At 10 feet from the cables the induced electric field falls below 2.6 μV/m.

Summary and Discussion

Magnetic Field

The geomagnetic field in Lake Champlain and the alterations to that field calculated in the vicinity of the NECPL cables are all far below the ICNIRP standard for human exposure to static magnetic fields (~0.1% of the general public exposure limit). The opportunity for human exposure to magnetic field levels above that of the geomagnetic field in Lake Champlain would be extremely limited and short-term.

Magnetic fields diminish quickly with distance, so the potential environmental effect of the underwater cables in Lake Champlain is largely restricted to a distance of approximately 10 feet on either side and above the cables.

Trench Configuration (Case T)

The cables will be trenched 3 feet or more into the lakebed with the cables strapped together and lying vertically atop one another for approximately half the route. In this configuration the total magnetic field at 1 foot above the lakebed over the cables will decrease by 156 mG or increase by 208 mG (northward power flow on the top cable) as shown in Table 3. At 10 and 19 feet above the lakebed, the maximum deviations (positive or negative) from the ambient geomagnetic field will be 18.4 mG and 6.4 mG, respectively.

At 10 feet to either side of the cables at 1 foot above the lakebed, the maximum increase from the ambient geomagnetic field will be 25.0 mG or less (a 5% change). At 10 feet and 19 feet above the lake bed (and 10 feet to either side of the cables) the increase will be smaller, 16.6 mG and 6.3 mG, respectively. At 25 feet from the cables at any height above the lakebed, the maximum change to the geomagnetic field will be roughly 1% or less. While the magnitude of the shift in the total magnetic field is similar for both power flow cases (i.e., northward current flow on top and east cables as shown in Table 3 and northward current flow on bottom and west cables as shown in Table A-1 in Appendix A), the arithmetic sign of the deviation (a positive increase or negative decrease) varies depending on the direction of current flow.

Bedrock Configuration (Case B)

The change in the geomagnetic field above the cables for the cables laid directly on the lakebed is considerably greater compared to the buried configuration because of the closer proximity of the cables to the calculation reference locations. As shown in Table 3, at 1 foot above the lakebed over the cables, the magnetic field level is 4,540 mG for northward current on the east cable, but the decrease in the magnetic field with distance is rapid. At 10 feet to either side (at 1 foot above the lakebed), the change in the magnetic field is ≤ 44.1 mG (8% change from ambient) and at 10 and 19 feet above the lakebed the change in the magnetic field will be about 6 mG or less.

Compass Deflection

Mariners use a compass to visualize the alignment of the horizontal component of the earth's geomagnetic field for navigation. Boaters who may be using traditional compasses that rely on the earth's geomagnetic field may detect a small effect on compass readings above the cables in shallow water that will diminish quickly with distance. Compass readings and locations obtained from global positioning system (GPS) receivers would not be affected by the NECPL cables.

Assuming a boater was passing 19 feet over the lakebed (for the Case T), the maximum deflection would be less than 3 degrees directly over the cable and less within ±10 feet of the cable. Compass deviations in navigable water depths of 10 feet would be higher (8 degrees), but also would decrease rapidly with distance. At this height (10 feet) and a distance of 10 feet from the centerline of the cables, the compass deviation would decrease to 1.3 degrees or less. At locations where the lake is more than 150 feet deep, the cables would not be buried, but the calculated compass deflection would be less than 1 degree.

Electric Field Induction

The voltage on the NECPL cables will not produce an electric field in the marine environment because of shielding by the metallic sheathing on the cables. The movement of electric charges, however, in the ambient environmental magnetic field of the earth or as altered by the presence of a DC submarine cable gives rise to an induced electric field.

Magnetic Fields and Aquatic Life

Aquatic organisms with known ability to detect electric and magnetic fields are uncommon in Lake Champlain; however, both the American eel and the lake sturgeon are able to detect such fields. Because of the presence of such fish in the lake, we reviewed their capability to detect alterations in the geomagnetic field around the NECPL cables. For such species, there is greater evidence that they respond to electric fields rather than static magnetic fields.

Aquatic organisms produce weak electric fields that are transmitted though the surrounding water. Certain elasmobranch predators (sharks, rays) and sturgeon can detect these electric fields via electroreceptors, and use these signals to detect prey and identify conspecifics during mating seasons. This capability in elasmobranchs appears quite early in development (Wueringer et al., 2012). Some aquatic organisms are believed to use the earth's magnetic field as a positioning and orienting cue; this can be especially critical for fish that migrate over long distances, such as salmon. These geomagnetic field-detecting organisms contain special organs that allow them to detect these fields. Eels (*Anguilla anguilla*) can detect the presence of geomagnetic fields apparently as a result of magnetic material incorporated into their skeletal system, primarily in the skull and vertebrae. Fish, including those in the genus *Oncorhnychus* (rainbow trout and several salmon) and sturgeon, orient to magnetic fields via magnetite-magnetoreceptor cells located in the nose (Gill et al., 2012). Additionally, some elasmobranchs may detect variations in geomagnetic fields and use this to orient during long-range foraging trips.

Because of the importance of electric and magnetic sensing abilities to a number of aquatic species, questions have been raised as to whether the introduction of magnetic fields from buried underwater power cables may interfere with normal biological functions. A comprehensive 2011 review of the literature commissioned by the Bureau of Ocean Energy Management, Regulation, and Enforcement concluded that some species of marine organisms are capable of detecting DC electric and magnetic fields, which appear relevant for prey detection or navigation (Normandeau et al., 2011). The research reviewed did not show that exposures to DC magnetic fields from anthropogenic sources have deleterious effects at individual or population levels.

To update this review with a focus on exposures to DC magnetic and electric fields such as those produced by NECPL described above, a search of the literature since 2010 was performed.[8] The results of relevant toxicologic and behavioral studies are summarized below. Because lake sturgeon are listed as an endangered species in the State of Vermont, and appear to be able to detect electric and magnetic fields as do elasmobranchs, particular attention was given to this species in this summary. Overall, the research does not indicate that changes in the geomagnetic magnetic field around the NECPL cables would be harmful to aquatic species including those with the capability to respond to electric and magnetic fields in the ambient environment.

Toxicologic Observations

The Normandeau et al. (2011) literature review did not indicate that DC magnetic fields have toxic effects on marine species. The study in this review that examined the effect of the highest exposures (3.7 mT, i.e., 37,000 mG) over the longest time (7 weeks) was Bochert and Zettler (2004). The authors exposed blue mussels (*Mytilus edulis*), North Sea prawn (*Crangon crangon*), isopods (*Saduria entomon*), round crab (*Rhithropanopeus harrisii*), and flounder (*Plathichthys flesus*), and determined that chronic exposure caused no increased mortality. In addition, mussels were exposed during their 3-month reproductive period, with no observed adverse effects to gonadal tissues.

A more recent study examined a wider range of species during early and late developmental stages (Woodruff et al., 2011). This study compared juvenile coho salmon (*Oncorhynchus kisutch*), Atlantic halibut (*Hippoglossus hippoglossus*), California halibut (*Paralicthys californicus*), rainbow trout (*Oncorhynchus mykiss*), and Dungeness crab (*Metacarcinus magister*) following short and longer term exposures to sham or 0.1 mT-3 mT (i.e., 1,000 mG-

8 The literature search was conducted for all of 2010 to the present since the Normandeau et al. (2011) literature review included studies through 2009 and a only a few months of 2010. Several of the studies included in the Normandeau et al., review are also discussed here.

30,000 mG) static magnetic fields. The authors reported no statistically significant effects of 0.1 and 3 mT magnetic field exposures on the alarm response of coho salmon or on cortisol or melatonin indicators of stress. Magnetic field exposure at 3 mT did not affect the fertilization, hatching rates, or average developmental scores of rainbow trout. The size and developmental stages of Atlantic halibut were not significantly affected by constant 3 mT magnetic field exposure, and significantly fewer magnetic-field-exposed fish died over a 25-day period versus controls. No effect of exposure to a 3 mT magnetic field or the survival, length, or eye development of California halibut was observed. Given these results the authors concluded:

> Given the lack of statistically significant behavior, growth, or exposure marker responses in the species tested in FY 2010 and FY 2011, there is no reason to believe that EMFs [electric and magnetic fields] associated with MHK [marine and hydrokinetic] devices or cables will result in adverse impacts at individual, community, or population levels for the species evaluated in this study. (p. 3.15)

Although there is a large body of research on the response of a variety of marine organisms to a wide range of electric and magnetic field intensities, it does not indicate that toxic effects of exposures are of concern. This is illustrated by the studies noted above in which short and longer term exposures at magnetic field levels 7-fold to 8-fold higher than that produced by the NECDL cables at full loading did not produce adverse effects on health or behavior measures.

Behavioral Observations

Given that a magnetic field detection capability supports specific types of behavior, questions have been raised as to whether changes in the ambient geomagnetic field would result in population level impacts (i.e., through reduced feeding or altered migratory routes). The review of the literature below focuses on the biological responses of representatives of these key aquatic species to experimental and natural electric and magnetic fields. The relevance of these studies to species in Lake Champlain may be limited by differences from taxa studied elsewhere but nonetheless are helpful in assessing the likelihood that some species in Lake Champlain can detect and respond to electromagnetic stimuli. It should be noted that salt water is a better conductor of electric fields than freshwater, so studies conducted with marine organisms in salt water will provide a conservative estimate of the sensitivity of electromagnetically-sensitive organisms.

Sturgeon and Elasmobranchs

The significance of induced electric fields in Lake Champlain pertains particularly to bony fishes, including sturgeon and eel, which have evolved sensory organs capable of detecting very weak electric fields. In contrast to the static magnetic field that is the focus of research on orientation and directional behaviors of a number of other aquatic organisms, research on the significance of electric field detection for these species with electroreceptors has focused more on prey detection, identification of predators, and social behavior.

The reported behavior of sturgeon indicates that they can detect alternating current (AC) bioelectric fields from fish or simulated electric fields with similar intensities and frequencies (1-10 Hertz) to those emitted by fish and other marine organisms. The characteristics of their electrosensory organs suggest that the detection of ambient DC electric fields produced by Lorenz forces also may be possible.

Prey-seeking behavior initiated by bioelectric or simulated dipole electric fields has been reported for multiple aquatic species (see multiple references in Normandeau et al., 2011). However, this response is best documented for elasmobranch species (sharks, rays, skates). In a review of the literature, Bedore and Kajiura (2013) found that elasmobranchs respond to electric fields in the range of 4 to 50 nanoVolts per centimeter (nV/cm) (i.e., 0.4-5 μV/m) over a detection distance of less than 50 centimeters. Conceptually, this indicates that species using bioelectric signals for prey detection must be in close proximity to the signal source. Similar to elasmobranchs, sturgeons have been shown to use weak electric fields to identify and locate potential prey. Zhang et al. (2012) demonstrated that Siberian sturgeon (*Acipenser baerii*) responded most strongly to an aluminum pole with a peak-to-peak signal of 90 microvolts (μV), whereas a signal of 15 μV induced no feeding behaviors. Feeding strikes, however, were equally likely to occur in response to bioelectric cues as olfactory stimulation, thus confirming that feeding behaviors are induced by multiple factors, not electric signals alone. The responses of the sturgeon to these metal rod stimuli were about 100-fold less than to the electric fields produced by live prey fish.

Electrophysiological measurements by Zhang et al. (2012) on the response of the sturgeon's electrosensory neurons showed increasing activity as the strength of the applied DC or 5 Hertz AC electric field approached 100 microvolts per centimeter (µV/cm). Conversely, juvenile Atlantic sturgeon (*Acipenser oxyrhynchus*) avoided a block of lanthanide metal (a presumed source of an unmeasured electric field and perhaps products of catalytic chemical reactions). Avoidance behaviors, however, were only evident in actively feeding fish, while resting individuals exhibited no avoidance of the electric field source (Bouyoucos et al., 2014).

It seems possible for sturgeon to detect alterations in the electic field directly over unburied cables (23.5 µV/m), but the salience of this change would diminish at distances beyond 10 feet from the cables at which the induced electric field falls below 2.6 V µV/m. As a result, the increment in the ambient marine electric field from buried or unburied cables would not be a unique or novel stimulus nor strong enough to produce adverse physiological responses.

Nevertheless, the question remains as to whether the small increment in the local ambient electric field might elicit specific behavioral responses (e.g., attract sturgeon or other species with receptors that detect electric fields). Since the induced electric field from water flow in a magnetic field is essentially a static DC electric field, it does not seem to be a sufficiently powerful stimulus to foster feeding behavior as is reported for the low frequency AC fields that distinguish the bioelectric fields of prey and other fish. Rather than strong feeding responses associated with AC electric stimuli, the electric fields from static DC sources (DC cable and corrosion potentials) may elicit temporary investigatory behavior as has been seen in anecdotal observations of sharks (Tricas and McCosker, 1984) or far weaker feeding responses as reported in experimental studies of sturgeon (Zhang et al., 2012). Hence, the induced electric field resulting from water flow or sturgeon swimming in the static magnetic field in Lake Champlain may be analogous to the galvanic electric fields produced by the corrosion potentials from pilings, ships, gas and petroleum pipelines, and virtually all sunk or constructed metal infrastructure.

Despite their reliance on natural electric and geomagnetic fields for prey detection and long-range orientation, sturgeons are unlikely to be adversely impacted by the electromagnetic fields generated by the NECPL cable system. In general, individuals must be in close proximity to field sources, and even when detected, the effects on behaviors are apparently minor and transitory (Normandeau et al., 2011).

Altogether, the research is consistent with the idea that if any behavioral response of sturgeon to the induced DC electric field from the NECPL cable system occurs, it is more likely be an investigative response (temporary and time-limited because of habituation) than a feeding response associated with a low frequency AC field such as the bioelectric electric field produced by fish prey that would be more persistent.

Migratory Fish and Eels

Migratory fish and eels use the earth's geomagnetic field cues to guide long-distance movements. Carp were observed to align along a north-south axis following capture and containment in circular tubs (Hart et al., 2012). Use of a biologic magnetic compass may be of specific importance for eel orientation in areas of low current or in oceanic systems (Durif et al., 2013); however, Westerburg and Begout-Anras (1999) tracked the movement of *Anguilla anguilla* eels in the vicinity of an underwater monopolar HVDC cable (which produces a magnetic field over a greater distance than the bipolar configuration proposed for NECPL), and determined that there was no evidence that the presence of the cable and resulting magnetic field deterred eels from traversing the cable area. The authors concluded that "the cable was unlikely to be an obstacle that could influence the escapement of the eels" (Westerburg and Begout-Anras, 1999)

Laboratory experiments with rainbow trout (*Oncorhynchus mykiss*) indicate that fish can perceive magnetic field direction and intensity in the absence of ambient light (Hellinger and Hoffman, 2012). The authors noted that this magnetic sense is likely used in conjunction with other types of cues, including olfactory and visual, to accomplish both long-range migration and short-range movements. Putman et al. (2014a) examined the relative importance of geomagnetic and olfactory imprinting in the long-distance homing behaviors of sockeye and pink salmon. Researchers determined that the majority of imprinting behavior resulted from geomagnetic signals, although other factors including temperature and olfactory cues did contribute to salmon homing. They also noted, however, that the inland-spawning sockeye salmon responded better to olfactory cues than pink salmon, which spawn offshore. In these studies chronic exposure to a distorted magnetic field was required to cause a prolonged change in the geomagnetic orienting behavior of juvenile steelhead trout (Putnam et al., 2014b); chronic exposures to young fish are not predicted under field conditions associated with the proposed project. Further, the available literature indicates that transitory exposures to altered geomagnetic fields produce only transitory effects and that fish return to pre-programmed responses to the geomagnetic field once they are removed from the distorted magnetic field (Taylor, 1986).

In a review of the literature, Gill et al. (2012) reported that salmonid embryos and fry reared in artificial magnetic fields exhibited altered swimming orientation, and that prolonged exposure to a magnetic field of 0.62 mT [6,200 mG] altered hormone levels in brook trout (*Salvelinus fontinalis*). The biological and ecological implications of these observed effects, however, were not explicit, and further, prolonged or chronic exposures are not expected at the Project site. Taylor (1986) reported that juvenile Chinook salmon exhibited altered axial orientation when exposed to magnetic signals with a 90 degree shift in the horizontal component versus the earth's geomagnetic field. After the normal geomagnetic signal was restored, however, fish exhibited normal axial orientation, indicating that the responses to modified geomagnetic fields are reversible once fish are removed from the field (Taylor, 1986).

Static magnetic fields constitute critical environmental cues for some diadromous fish species. These fish perform migrations through the use of geomagnetic cues, and therefore these fish and others with similar life histories may detect and perhaps respond to alterations in the ambient geomagnetic field around submarine cables. Regarding detection of induced electric fields, the Gill et al. (2012) review of the literature indicates that fish are likely respond to ambient electric fields in their environment induced by tidal movements between 8 and 25 µV/m [i.e., 80-250 nV/cm].

In the context of the environment around the proposed NECPL cables, the calculations of the induced electric field for a typical high water flow case of 4.8 cm/s suggest that migratory fish may be unlikely to detect induced electric fields by current flows through the ambient geomagnetic field (2.6 µV/m) or over buried NECPL cables (3.7 µV/cm) but could make use of the geomagnetic field by itself for orientation and navigational purposes.

Invertebrates

Compared to vertebrates and elasmobranchs, relatively little is known about aquatic invertebrate use of electric or magnetic fields in migration, orientation, or prey identification. In Lake Champlain, resident invertebrate megafauna include several mussel (cylindrical papershell, black sandshell, and giant floater) and crayfish species. Behavioral studies have been conducted with a nudibranch and a spiny lobster, both marine species. As such, extrapolation to freshwater aquatic invertebrate species of interest may be difficult.

The marine nudibranch *Tritonia spp*. contains a number of electrosensitive receptors that allow it to respond to geomagnetic signals. Pavlova et al. (2011) demonstrated that these receptors are dispersed among both the primary and peripheral nervous system. These allow nudibranch to orient towards and travel according to certain preferred geomagnetic headings, and guide excursions between shallower and deeper areas (Cain et al., 2005). It is possible that freshwater gastropods may have similar receptors and responses to geomagnetic cues.

Spiny lobsters undertake extensive nighttime foraging trips; in order to return to home dens, individuals utilize several cues, including landmark recognitions and geomagnetic signals, to orient along return trips (Cain et al., 2005). Spiny lobsters removed from home areas and released kilometers away were capable of re-orienting and homing using geomagnetic cues. Even when lobsters were transported in magnet-lined containers, they were able to appropriately detect and react to geomagnetic cues once removed from the artificial magnetic field (Boles and Lohmann, 2003). Similarly, additional studies with spiny lobsters indicated that reversal of the horizontal component of the earth's geomagnetic field altered lobsters' orienting abilities, while vertical field reversal did not (Lohmann et al., 1995).

Given that both lobsters and nudibranch are demersal invertebrates, it is possible that these species may be able to detect alterations in the geomagnetic field around buried submarine cables. Available literature indicates, however, that lobsters re-establish geomagnetic positioning abilities once removed from artificial magnetic fields. Therefore, as potential exposure areas are very small and the likely effect is transient, it is unlikely that populations of resident geomagnetic-sensitive invertebrates, if present in Lake Champlain, will be adversely affected.

Conclusions

Based on a review of the relevant scientific literature, the change in the background geomagnetic field produced by the NECPL DC cables would not cause adverse impacts on resident populations of aquatic species. In fact, the information indicates that:

1) The potential for toxic effects of altered magnetic or induced electric fields appears quite low or non-existent;

2) The range of detection for induced electric fields reported in the literature (as may be induced by fish movement) is small, less than 50 centimeters in most cases and is unlikely to extend around the NECPL cables beyond 10 feet where magnetic fields and induced electric fields approach background levels;

3) Fish responses to temporary or spatially limited changes in the geomagnetic field are reversible, with aquatic species able to successfully resume pre-exposure orientations after passing over or through areas with geomagnetic changes; and

4) Orientation and migratory behaviors result from an integration of multiple cues. The cable will be buried in waters with depths less than 150 feet where fish are most prevalent and the resulting change in the maximum magnetic field will be very small even directly over the cable. At greater depths where the cable is will not be installed under the lake bottom, the maximum magnetic field will be considerably higher within ± 3 feet of the cable centerline but at 10 feet, will be of the same order of magnitude as cables buried 3 feet or more. Where the cables self-bury to a depth of say 1 foot, the change in the magnetic field will be less and the prevalence of fish lower.

Further, calculations at maximum load on the NECPL cable show that the area most affected by the NECPL cable (~10 feet around the cable) is very small relative to the area of Lake Champlain through which the cable will traverse. This suggests that the probability of resident aquatic species encountering areas with significantly altered magnetic fields associated with the buried cable is very low.

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Limitations

At the request of TDI-NE, Exponent calculated the magnetic field levels from a ±320-kV segment of a DC transmission line in Lake Champlain with the capacity to carry approximately 1,000 MW of electricity. This report summarizes work performed to date and presents the findings resulting from that work. In the analysis, we have relied on information provided to us by staff of TDI-NE and its consultants with respect to parameters and configurations of the transmission line. The relevance of these results to fish and other aquatic life was evaluated by reference to published neurobiological and marine research. The findings presented herein are made to a reasonable degree of engineering and scientific certainty. Exponent reserves the right to supplement this report and to expand or modify opinions based on review of additional material as it becomes available, through any additional work, or review of additional work performed by others.

The scope of services performed during this analysis may not adequately address the needs of other users of this report, and any re-use of this report or its findings, conclusions, or recommendations presented here are at the sole risk of the user. The opinions and comments formulated during this assessment are based on observations and information available at the time of the investigation. No guarantee or warranty as to future life or performance of any reviewed condition is expressed or implied.

Appendix A – Magnetic field and Compass Deflection Calculations

Table A-1. Magnetic field magnitude deviation (mG) from 535.44 mG geomagnetic field, above lakebed and for offsets from centerline of bipolar DC circuit with north-south orientation of cables

Cable burial depth and phasing	Height above lakebed (feet)	Distance from circuit centerline							
		-50 feet	-25 feet	-10 feet	Max + deflection	Max - deflection	+10 feet	+25 feet	+50 feet
3 feet (northward current on top)	1	0.1	1.6	25.0	207.5	-156.2	-28.4	-2.8	-0.4
	10	0.7	4.3	16.6	18.4	-16.2	-15.6	-4.9	-1.0
	19	1.0	4.0	6.3	6.4	-5.7	-5.3	-4.1	-1.2
3 feet (northward current on bottom)	1	-0.1	-1.5	-22.9	188.3	-174.9	30	2.9	0.5
	10	-0.7	-4.3	-16.5	16.5	-18.1	15.8	4.9	1
	19	-1	-4	-6.2	5.7	-6.3	5.4	4.1	1.2
0 feet (northward current west side)	1	1.8	7.2	44.6	3538.9	0.1	43.1	7.1	1.8
	10	1.7	4.9	2.6	6.7	-44.7	-1.6	4.1	1.5
	19	1.3	1.7	-4.7	1.8	-12.4	-6.2	0.8	1.1
0 feet (northward current east side)	1	-1.8	-7.2	-44.1	4539.7	-232.6	-42.3	-7.1	-1.8
	10	-1.7	-4.9	-1.6	45.2	-6.5	2.6	-4.1	-1.5
	19	-1.3	-1.6	4.8	12.5	-1.8	6.3	-0.8	-1.1

Table A-2. Compass deflection (degrees) from 14.35° W declination, above lakebed and offset from centerline of bipolar DC circuit with north-south orientation of cables

Cable burial depth and phasing	Height above lakebed (feet)	Distance from circuit centerline							
		-50 feet	-25 feet	-10 feet	Max + deflection	Max - deflection	+10 feet	+25 feet	+50 feet
3 feet (northward current on top)	1	-0.6	-2.1	-9.1	47.8	-11.4	-9.1	-2.1	-0.6
	10	-0.5	-1.0	1.3	8.0	-1.0	1.3	-1.0	-0.5
	19	-0.3	-0.2	1.6	2.9	-0.4	1.6	-0.2	-0.3
3 feet (northward current on bottom)	1	0.6	2.1	8.4	10.4	-68.5	8.4	2.1	0.6
	10	0.5	1.0	-1.3	1.0	-8.6	-1.3	1.0	0.5
	19	0.3	0.2	-1.6	0.4	-2.9	-1.6	0.2	0.3
0 feet (northward current west side)	1	<0.1	0.2	2.7	72.2	-100.8	-2.8	-0.2-0.2	<0.1
	10	0.2	1.3	6.4	8.3	-8.9	-6.8	-1.3	-0.2
	19	0.3	1.3	2.4	2.4	-2.4	-2.4	-1.3	-0.3
0 feet (northward current east side)	1	<0.1	-0.2	-2.6	72	-100.6	2.6	0.2	<0.1
	10	-0.2	-1.3	-6.8	8.3	-8.9	6.4	1.3	0.2
	19	-0.3	-1.3	-2.4	2.4	-2.4	2.4	1.3	0.3