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Magnetic Field Assessment for Proposed Vermont Green Line Subterranean and Submarine Cables

Vermont Facilities

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Prepared for

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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
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
VGL or Project	Vermont Green Line Project

Executive Summary

Vermont Green Line Devco, LLC, is proposing the Vermont Green Line (VGL or Project), a high-voltage direct-current (DC) electric power transmission system that will connect the New York Power Authority's Plattsburgh Substation to the Vermont Electric Power Company's New Haven Substation. The line will run from Beekmantown, New York, along underwater and underground routes to New Haven, Vermont.

The transmission line will be comprised of two solid dielectric cables with a nominal operating voltage of ±150 kilovolts and a system capacity of 409 megawatts of electricity. When in operation, the system will produce a DC static magnetic field around the cable with strength similar to the earth's geomagnetic field. This static field is not the same as the alternating current (AC) magnetic field associated with most equipment connected to our electric grid, which is sometimes referred to as "EMF".

This report summarizes Exponent's calculations of static magnetic fields associated with the operation of the DC transmission line in five configurations (three in Lake Champlain and two on land). The cable system is anticipated to have approximately 9 MW of capacity loss over the total length of the line such that the total delivered capacity for the Project will be 400 MW. The total capacity of 409 MW was assumed for the modeling of the static magnetic field to yield conservative estimates of the maximum magnetic fields from the cable system.

Results for these five configurations describe the range of changes to the ambient geomagnetic fields associated with the proposed Project. In addition to the change to the ambient geomagnetic field the transmission line will affect the level of induced electric fields and potentially compass deflection.

The effect of the transmission line will be limited largely to the area immediately surrounding the VGL cables. The calculated deviations in the static magnetic-field, induced electric field, and compass deflections fall off rapidly with distance for most configurations of the DC cables. The highest total magnetic field on land over the VGL cables is 782 milligauss (mG), which reflects the contribution from the ambient geomagnetic field of 535 mG and 247 mG from the

cables, and is far below the International Commission for Non-Ionizing Radiation Protection's standard for human exposure to static magnetic fields (< 0.1% of the general public exposure limit of 4,000,000 mG) for all configurations considered. The highest calculated magnetic field is also well below the applicable medical device standard of 10,000 mG for exposure to static magnetic fields from those devices.

Likewise, potential changes in compass readings above the buried cables will diminish quickly with distance. In water depths of 10 feet or more, the maximum compass deviation would be 3 degrees directly over the cable and would decrease to less than1 degree at a distance of 10 feet or more from the circuit centerline. Navigational instruments that obtain compass readings and locations from global positioning system receivers would not be affected by the VGL cables.

The induced electric field produced by the movement of electric charges in water at a velocity of 4.8 centimeters per second, typical of Lake Champlain, is less than 18 microvolts per meter at a height of 1 foot over the lakebed and also decreases rapidly with distance. This is in the range of the electric field induced in waters due to the ebb and flow of coastal tidal currents in the presence of earth's static geomagnetic field, 5-75 microvolts per meter.

Between the converter station and the New Haven Substation in New Haven, Vermont, an AC transmission line will be buried underground for a distance of approximately 1,000 feet. This ancillary transmission line produces AC magnetic fields above ground over the buried cables at levels far below international standards and is discussed in Appendix B in detail.

An assessment of the relevant scientific literature on species of freshwater fish in Lake Champlain with high priority conservation value and other medium value fish species with known or possible abilities to sense static magnetic and electric fields did not provide scientific evidence that fields from the cables in Lake Champlain at very low calculated levels would have adverse physiological or behavioral effects on these fish populations.

Introduction

Vermont Green Line Devco, LLC, is proposing the Vermont Green Line Project (VGL or Project). The Project is a high-voltage direct-current (DC) electric power transmission system that will connect the New York Power Authority's Plattsburgh Substation to the Vermont Electric Power Company's New Haven Substation. The line will run from Beekmantown, New York, along underwater and underground routes to New Haven, Vermont.

The transmission line will consist of two solid dielectric cables with positive and negative polarity and contain no fluids or gases. The diameter of the cable will depend on the configuration and will be either 97 millimeters (mm) or 111 mm. The nominal operating voltage of the line will be ±150 kilovolts (kV), and the system will be capable of delivering 409 megawatts (MW) of electricity.

Between the converter station and the New Haven Substation, an ancillary alternating current (AC) transmission line will be buried underground for a distance of approximately 1,000 feet. This ancillary transmission line produces AC magnetic fields above the cables at levels far below international standards and is discussed in Appendix B in detail.

To assess and describe the magnetic-field exposures associated with the proposed Project, Exponent calculated static magnetic flux densities (referred to hereafter to as magnetic fields) associated with the operation of the underground cables on land and the underwater cables in Lake Champlain for five scenarios that represent the range of expected magnetic-field changes. These calculated magnetic fields represent the total static magnetic field that would be measured around the cables from the joint contributions of the cables and the earth's geomagnetic field after the completion of the Project. Although the metallic sheathing around each cable shields the environment from the electric field from the cables, the flow of electric charges in water flow or moving organisms in a static magnetic field (whether from the earth or a combination of the earth and the VGL cables) induces a very weak static electric field, which was calculated as well.

To assess the effects of potential human exposure, the calculated values of magnetic fields were compared to established health-based standards. These standards would apply to exposures of humans in both terrestrial and aquatic environments. The potential significance of induced electric fields and changes in the geomagnetic field for fish was evaluated based on a review of the relevant scientific literature.

Static Magnetic-Field Standards

The State of Vermont, the State of New York, and the federal government have not established standards for static magnetic fields or DC transmission lines.

The International Commission on Non-Ionizing Radiation Protection (ICNIRP), however, has a recommended a general public exposure limit of 4,000,000 mG for static magnetic fields (ICNIRP, 2009).[1,2] This exposure limit encompasses large safety factors to preclude any established biological effects.

For individuals with implantable medical devices (such as pacemakers and pulse generators) the exposure limit for static magnetic-field exposure to these devices is determined by other standards such as Standard ANSI/AAMI/ISO 14117:2012, which specifies that no change in the function of the pacemaker or other implantable device should occur at static magnetic-field levels less than 1 millitesla (mT) (i.e., 10,000 mG). After exposure to static magnetic fields up to 500,000 mG (50 mT), the standard requires that the functions of an implantable device not be affected after discontinuation of the exposure.[3]

As demonstrated in the following sections of this report, the static magnetic fields associated with Project operation would be well below the limits set out in these standards designed to protect public health and safety.

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[1] There are differences between static fields and AC 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 are needed for each of these frequencies. Because of these differences, the ICNIRP limit for static magnetic-field exposure is set at a far higher level than its 2010 limit for 60-Hertz AC magnetic fields (2,000 mG).

[2] An ancillary AC transmission line between the converter station and the New Haven Substation will be a source of AC magnetic fields and is discussed in Appendix B in detail.

[3] The ANSI/AAMI/ISO 14117:2012 is a recognized a consensus standard by the Food and Drug Administration.

Methods

Magnetic Field

When DC current flows through a conductor, a static magnetic field is induced. This field can be calculated by the application of the Biot-Savart law, which is derived from fundamental laws of physics and computes the magnetic field caused by a flow of charges through a conductor. Application of the Biot-Savart Law is particularly appropriate for long straight conductors such as the VGL cables.[4]

Magnetic-field calculations were performed for four different VGL configurations summarized in Table 1. Configuration 1 describes scenarios where the cables are to be installed underground (Configuration 1a) and under water (Configuration 1b) by horizontal-directional drilling (HDD). Cables installed by HDD comprise a short length of route (<0.2 miles total). In both Configuration 1a and 1b, the two cables (positive and negative conductors) are calculated for a horizontal separation of 30 feet (center to center). The cables installed by HDD were modeled as 97 mm in outside diameter and will be installed in high density polyethylene conduit.

Configuration 2 is representative of the upland trench portion of the route that would run for a length of approximately 20 miles, linking the converter station in New Haven, Vermont to the underwater cables. In Configuration 2, the cables were modeled for a horizontal separation of 1.5 feet (center to center) using the same 97 mm diameter cable installed in a polyvinyl chloride conduit 4 feet below ground.

Configuration 3 represents the underwater portion of the route where the cables are jet-plowed below the lakebed in shallow water areas (<150 feet in depth). Cables in this configuration are proposed to run for a total length of approximately 4.5 miles.

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[4] $|B| = \mu_0|H| = \mu_0 I/2\pi r$, where B is the magnetic flux density, μ_0 is the magnetic permeability of a vacuum, I = current, and r = the distance from each cable conductor.

Configuration 4 represents of the portion of the route where the cables are laid on the lake bottom in deep water areas (>150 feet in depth). This configuration is proposed for a total length of approximately 35.6 miles. The cables used for Configuration 3 and Configuration 4 are 111 mm in diameter, bundled together, and modeled in a horizontal plane. For modeling purposes, a center-to-center distance between the cables was assumed 111 mm (i.e., the sum of radii of two adjacent cables).

Table 1. DC Cable Configurations 1-4*

	Configuration				
Conditions	**1a† Underground HDD**	**1b† Underwater HDD**	**2‡ Upland Trench**	**3 Jet Plow**	**4b§‡ Surface Laid**
Cable separation (center-center)	30 feet	30 feet	1.5 feet	Touching (0.37 feet)	Touching (0.37 feet)
Cable orientation	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal
Burial depth	15 feet	15 feet	4 feet	4 feet	0 feet
Electrical current direction	NW/SE	NW/SE	W/E	NW/SE	N/S
Cable diameter	97 mm	97 mm	97 mm	111 mm	111 mm
Height of evaluation	1 m (3.28 feet) above ground	1, 10, and 19 feet above lakebed	1 m (3.28 feet) above ground	1, 10, and 19 feet above lakebed	1, 10, and 19 feet above lakebed
Approximate length in Vermont	0.1-0.2 miles		13.2 miles	4.5 miles	33.9 miles

* The cable configurations were provided by TRC Solutions based on their consultations with marine cable installers and manufacturers.

† Configuration 1 is modeled as 1a and 1b in the magnetic-field report because of the use of this configuration both underwater and underground. The model is identical in both configurations and is evaluated only at different locations.

‡ Configuration 2 is entirely on land.

§ Configuration 4b was used for modeling the static magnetic field underwater at depths >150 feet. In portions of the underwater route the cables are expected to self-bury about 1 foot below the lakebed. In the companion Exponent assessment of thermal effects of the cables, these burial conditions are referred to as Configurations 4a (self-burial) and 4b (surface laid). Self-burial configuration 4a will produce lower magnetic fields at the surface of the lakebed and above (not modeled) than the surface-laid configuration.

Modeling was performed using the most conservative assumptions for the configurations. The loading of the two ±150-kV cables was assumed to be 1,370 amperes (A), a conservative estimate based on 409 MW of delivered power.[5] For underground configurations (1a and 2), the

[5] The cable system is anticipated to have approximately 9 MW of capacity loss over the total length of the line such that the total delivered capacity for the Project will be 400 MW. Conservative estimates of the maximum magnetic field from the cable system were based on the total capacity of 409 MW.

magnetic fields were calculated along a transect perpendicular to the route of the cables at a height of 1 meter above ground consistent with the recommendations of IEEE Standards C95.3.1-2010 and 644-2008. For the underwater configurations (1b, 3, and 4), magnetic fields were 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 magnetic-field levels likely to be encountered by aquatic life and boaters. In addition, because the direction of current flows on the (+) cable and the (–) cable is not known *a priori*, the magnetic-field levels were calculated for both possible directions of current flow.

In order to assess the change in the earth's ambient geomagnetic field due to the VGL cables, the center of Lake Champlain was selected as a location where the geomagnetic field could be used to represent the magnetic field along the entire Project route. This was a reasonable choice as the geomagnetic field does not vary sufficiently to affect the reported magnetic-field values and compass deflections by more than approximately 0.5%, a *de minimus* change. The value of the geomagnetic field at this location was obtained using the International Geomagnetic Reference Field (IGRF) Model.[6] 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 -14.38 degree declination (westward of geographic north) and a 69.42 degree inclination (downward).

Table 2. Geomagnetic magnetic field at coordinates 44.538102°N, 73.334639°W

Component	Geomagnetic field (in nanotesla [nT] and mG)		
Northern component	18,227.6 nT	=	182.27 mG
Eastern component	-4671.7 nT	=	-4.68 mG
Downward component	50114.4 nT	=	501.14 mG
Total geomagnetic field			535.30 mG

Source: http://www.ngdc.noaa.gov/geomag-web/#igrfwmm. Reported vales were calculated on February 8, 2016, using IGRF.

[6] Magnetic Field Calculators provided by National Centers for Environmental Information (http://www ngdc noaa.gov/geomag-web/#igrfwmm)

The earth's geomagnetic field and the magnetic field from the VGL cables are both static (i.e., not time varying to any appreciable extent) and are vector quantities (i.e., with a strength and a direction). Therefore, the vector addition of the two fields is needed to determine the total magnetic field (geomagnetic field + VGL 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 and only the total magnetic field surrounding the cables is shown in the following figures.

Compass Deflection

The interaction between a compass needle and the horizontal component of the geomagnetic field causes the needle to point toward the magnetic North Pole. To quantify the potential effect of the magnetic field of the cables on navigation using a compass, Exponent calculated the deviation of a compass reading near the VGL cables for each of the five modeling configurations from pre-installation conditions.

Induced Electric Field

The movement of electric charges in a magnetic field results in an induced electric field. The magnetic field can be the ambient geomagnetic field or the total magnetic field (cable + ambient geomagnetic). The induced electric field is calculated by applying Lorentz's law, 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 regions where the underwater VGL cable increases the static magnetic field above that of the ambient geomagnetic field in the water column over the cable, the electric field induced by the movement of charges in water will be increased as well. The induced electric field will depend on the speed and direction of charge movement of the water (or a fish) over the cable. In the following analysis, the speed of the water or a fish (in centimeters per second [cm/s]) is substituted for the magnitude of the velocity vector **v** in Lorentz's law.

Results

Magnetic Field Deviations

The estimated total static magnetic field due to the geomagnetic field and VGL cables in each of the five configurations is presented in this section. The direction of current flow on the cables that resulted in the maximum change in the geomagnetic field was used for all primary analyses of these configurations. Estimates of the magnetic field resulting from current flow on the cables in the opposite directions were lower and are summarized in Appendix A.

Configurations 1a and 1b correspond to the portion of the route installed by HDD for a short length (< 0.2 miles). Figure 1 illustrates the total magnetic field along a transect at a height of 1 meter above ground for Configuration 1a assuming northwestward current in the southwestern conductor. Figure 2 illustrates the calculated magnetic field at heights of 1 foot, 10 feet, and 19 feet above the lakebed for Configuration 1b assuming northwestward current in the southwestern conductor. Table 3 lists the resulting magnetic-field deviation from the geomagnetic field (535 mG) for Configuration 1a along the transect at distances 10 feet, 25 feet, and 50 feet from the cable centerline. Similarly, Table 4 lists the resulting magnetic-field deviation from the geomagnetic field (535 mG) for Configuration 1b.

Results of AC magnetic-field calculations for the ancillary transmission line are discussed in Appendix B in detail.

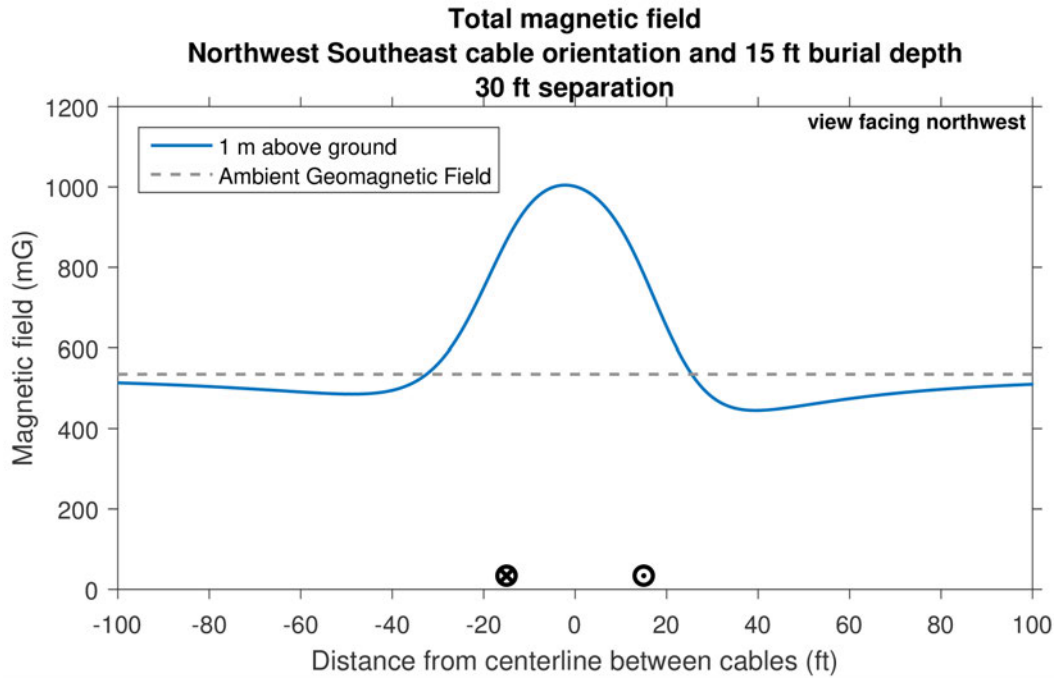

Figure 1. Total magnetic field − Configuration 1a (underground HDD).

Total magnetic field (cable + ambient geomagnetic) for DC cables oriented northwest-southeast, buried 15 feet underground, separated by 30 feet, with northwestward current in the southwestern conductor.

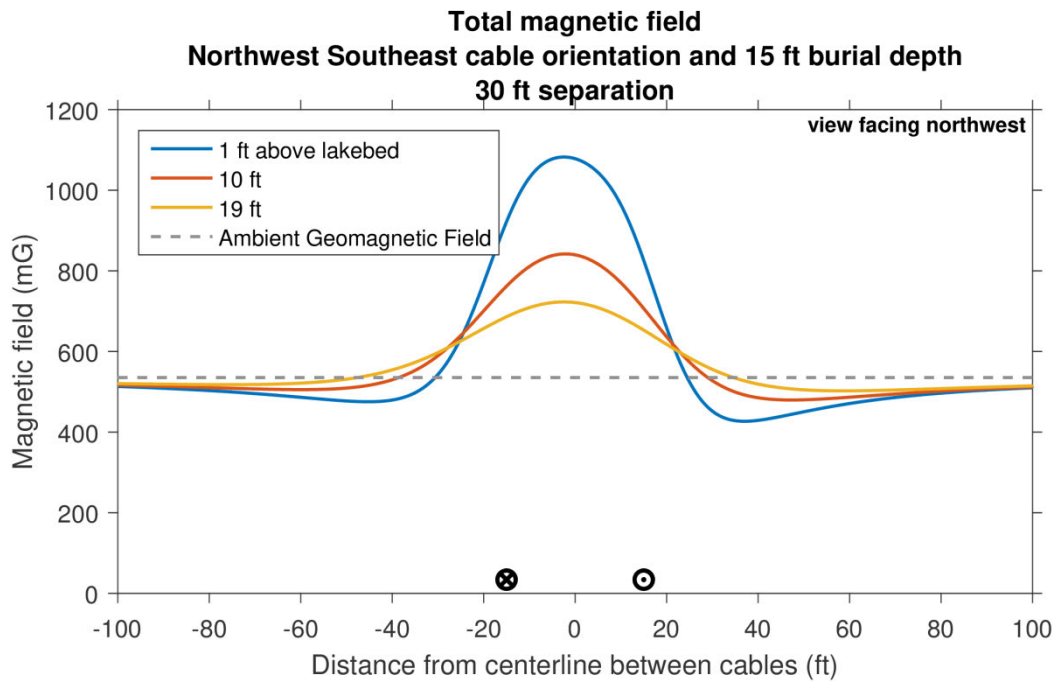

Figure 2. Total magnetic field − Configuration 1b (underwater HDD).

Total magnetic field (cable + ambient geomagnetic) calculated for DC cables oriented northwest-southeast, buried 15 feet under Lake Champlain, separated by 30 feet.

Configuration 2 corresponds to cables installed in an upland trench for approximately 20 miles of the route that is proposed to link the underwater cable to converter stations. Figure 3 illustrates the calculated total magnetic field along a transect at a height of 1 meter above ground assuming westward current in the southern conductor. Table 5 lists the resulting deviation of the total magnetic field from the geomagnetic field along a transect at distances of 10 feet, 25 feet, and 50 feet from the centerline between the two conductors. Results for an alternate scenario for Configuration 2, in which the westward current flows in the northern conductor, are provided in Appendix A.

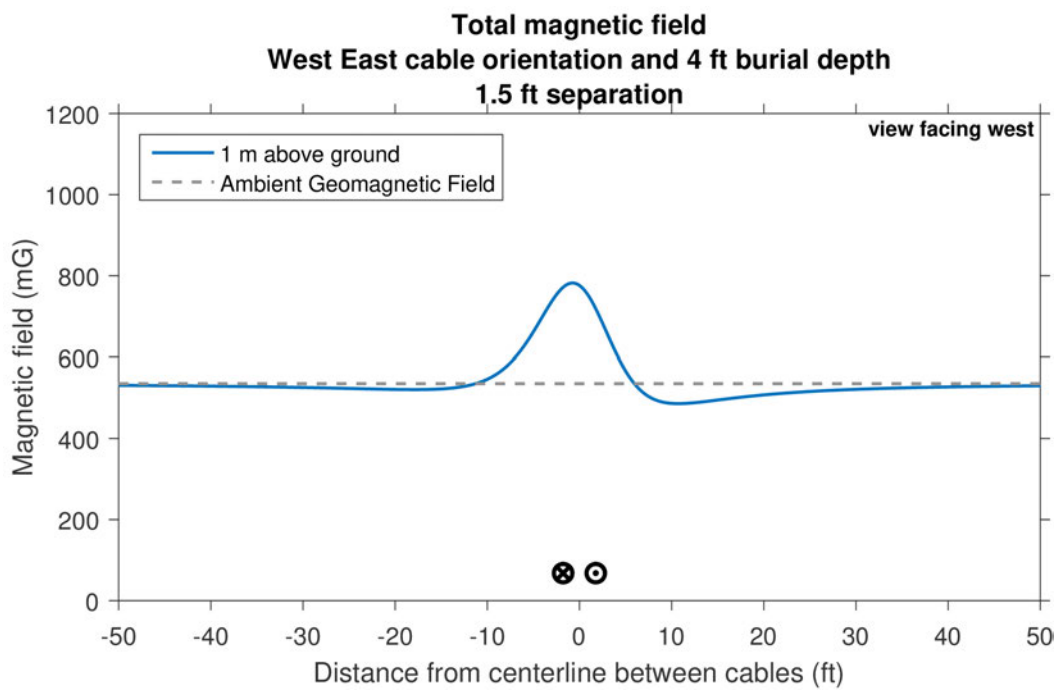

Figure 3. Total magnetic field − Configuration 2.

Total magnetic field (cable + ambient geomagnetic) calculated for DC cables oriented west-east, buried 4 feet underground, separated by 1.5 feet, with westward current in the southern conductor.

Configuration 3 corresponds to underwater portion of the route in shallow areas (< 150 feet deep). The cables are proposed to be installed using a jet plow and would run for a total length of approximately 4.5 miles. Figure 4 illustrates the calculated total magnetic field at heights of 1 foot, 10 feet, and 19 feet above the lakebed assuming northwestward current in the southwestern conductor. Table 6 lists the resulting magnetic field deviation from the geomagnetic field along transects at 10 feet, 25 feet, and 50 feet from the centerline between the two conductors. Results for an alternate scenario for Configuration 3, in which the northwestward current flows in the northeastern conductor, are provided in Appendix A.

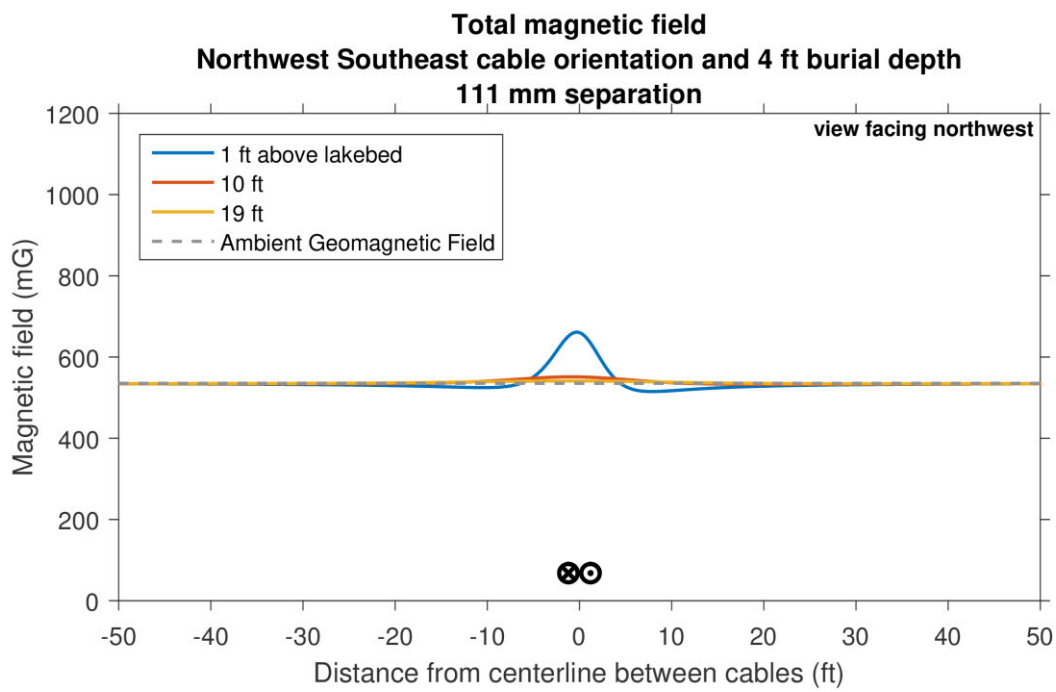

Figure 4. Total magnetic field − Configuration 3.

Total magnetic field (cable + ambient geomagnetic) calculated for DC cables oriented northwest-southeast, buried 4 feet underwater, separated by 111 mm, with northwestward current in the southwestern conductor.

Configuration 4 corresponds to the underwater portion of the route in deep water areas (> 150 feet deep). The cables are proposed to be surface laid and run for a total length of approximately 35.6 miles. Along most of the route the cable is expected to self-bury to a depth of approximately 1 foot. At these locations magnetic field levels above the lakebed would be lower than modeled here. The calculated magnetic field levels are therefore a conservative upper estimate of the magnetic field level along this portion of the route. Figure 5 illustrates the calculated total magnetic field at heights of 1 foot, 10 feet, and 19 feet above the lakebed assuming northward current in the western conductor. Table 7 lists the resulting magnetic-field deviation from the geomagnetic field along transects at 10 feet, 25 feet, and 50 feet from the centerline between the two conductors. Results for an alternate scenario for Configuration 4, in which the northward current flows in the eastern conductor, are provided in Appendix A.

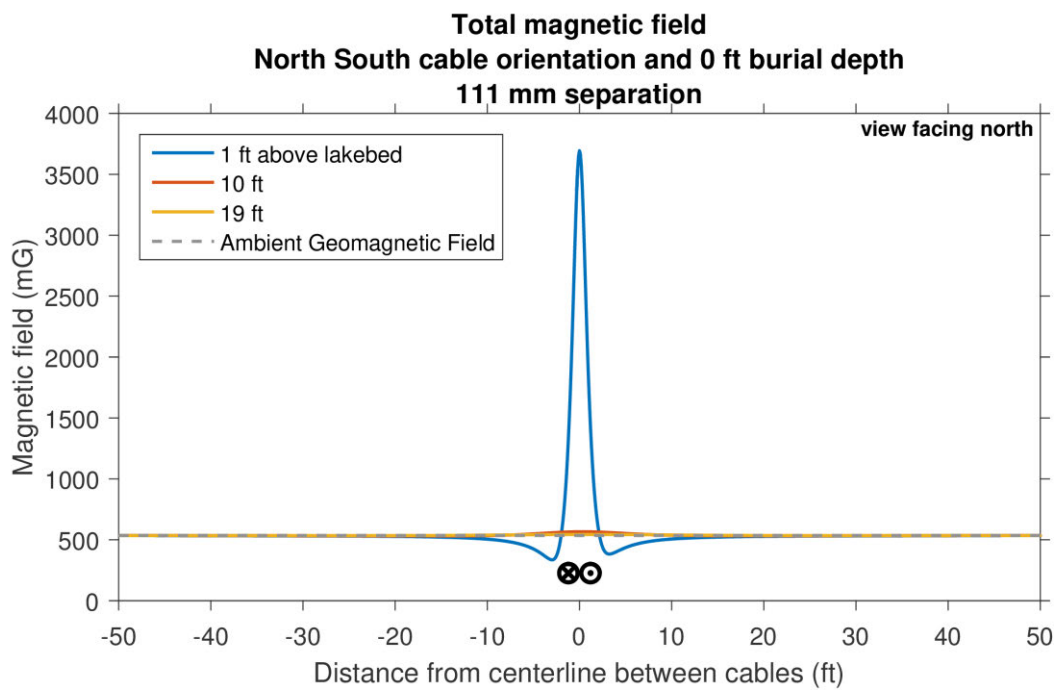

Figure 5. Total magnetic field − Configuration 4.

Total magnetic field (cable + ambient geomagnetic) or DC cables oriented north-south, lying underwater on the surface of the lakebed, separated by 111 mm, with northward current in the western conductor. Note that the y-axis scale is different than that in Figure 1.

Table 3. Configuration 1a − magnetic-field magnitude deviation (mG) from 535 mG geomagnetic field 1 meter above ground with DC cables in northwest-southeast orientation

	Distance from circuit centerline							
Cable burial depth and phasing	**-50 feet**	**-25 feet**	**-10 feet**	**Max + deviation**	**Max - deviation**	**+10 feet**	**+25 feet**	**+50 feet**
15 feet (northwestward current in the southwestern conductor)	-50	103	419	468	-91	360	7.4	-78

Table 4. Configuration 1b − magnetic-field magnitude deviation (mG) from 535 mG geomagnetic field above lakebed with DC cables in northwest-southeast orientation

		Distance from circuit centerline							
Cable burial depth and phasing	**Height above lakebed (feet)**	**-50 feet**	**-25 feet**	**-10 feet**	**Max + deviation**	**Max - deviation**	**+10 feet**	**+25 feet**	**+50 feet**
15 feet (northwestward current in the southwestern conductor)	1	-59	96	495	546	-109	428	-12	-86
	10	-27	104	274	306	-57	234	38	-56
	19	-5.0	90	173	187	-34	149	48	-32

Table 5. Configuration 2 − magnetic field magnitude deviation (mG) from 535 mG geomagnetic field 1 meter above ground with DC cables in west-east orientation.

	Distance from circuit centerline							
Cable burial depth and phasing	**-50 feet**	**-25 feet**	**-10 feet**	**Max + deviation**	**Max - deviation**	**+10 feet**	**+25 feet**	**+50 feet**
4 feet (westward current in the southern conductor)	-5.3	-13	9.6	246	-50	-50	-20	-6.3

Table 6. Configuration 3 − magnetic field magnitude deviation (mG) from 535 mG geomagnetic field above lakebed with DC cables in northwest-southeast orientation

		Distance from circuit centerline							
Cable burial depth and phasing	**Height above lakebed (feet)**	**-50 feet**	**-25 feet**	**-10 feet**	**Max + deviation**	**Max - deviation**	**+10 feet**	**+25 feet**	**+50 feet**
4 feet (northwestward current in the southwestern conductor)	1	-2.2	-5.1	-12	125	-21	-19	-5.8	-2.3
	10	-1.9	-2.4	4.3	15	-3.7	0.6	-3.6	-2.1
	19	-1.6	-0.7	3.0	4.9	-2.0	1.6	-1.8	-1.9

Table 7. Configuration 4 − magnetic-field magnitude deviation (mG) from 535 mG geomagnetic field above lakebed with DC cables in north-south orientation

		Distance from circuit centerline							
Cable burial depth and phasing	**Height above lakebed (feet)**	**-50 ft**	**-25 ft**	**-10 ft**	**Max + deviation**	**Max - deviation**	**+10 ft**	**+25 ft**	**+50 ft**
0 ft (northward current in the western conductor)	1	-2.3	-6.0	-31	3157	-201	-30	-5.9	-2.3
	10	-2.2	-4.4	-2.2	30	-5.5	0.6	-3.8	-2.1
	19	-1.9	-2.2	2.3	7.5	-2.3	3.3	-1.6	-1.8

Compass Deflection

The declination of geomagnetic field (i.e., the angle of magnetic north relative to geographic north) in the area of the Project is 14.38 degrees W. Compass deflections from this declination due to the five configurations are presented in this section. Positive compass deflection values correspond to counterclockwise deflections.

Figure 6 illustrates estimated compass deflections for Configuration 1a along a transect at 1 meter above ground assuming a northwestward current in the southwestern conductor. Table 8 lists the compass deflections along the transect at distances 10 feet, 25 feet, and 50 feet from the centerline between the two conductors. Results for an alternate scenario for Configuration 1a, in which the northwestward current flows in the northeastern conductor, are provided in Appendix A. Similarly, Figure 8 illustrates compass deflections and Table 10 lists the compass deflections at distances 10 feet, 25 feet, and 50 feet for Configuration 2 along a transect at a height of 1 meter above ground. The results for the alternate scenario for Configuration 2 are in Appendix A.

In Configurations 1b, 3, and 4, the cables are underwater and compass deflections were calculated for transects 1 foot, 10 feet, and 19 feet above the lakebed.[7] Figure 7, Figure 9, and Figure 10 illustrate the compass deflection for Configurations 1b, 3, and 4, respectively. Table 9, Table 11, and Table 12 list compass deflections at distances 10 feet, 25 feet, and 50 feet along the three transects for Configurations 1b, 3, and 4, respectively. The deflections corresponding to alternate scenarios for Configurations 1b, 3, and 4 with opposite current direction are provided in Appendix A.

[7] The water depth in each of these sections is 12-15 feet. Therefore, a boat is unlikely to encounter compass deflections values calculated at the 1-foot and 10-foot depth.

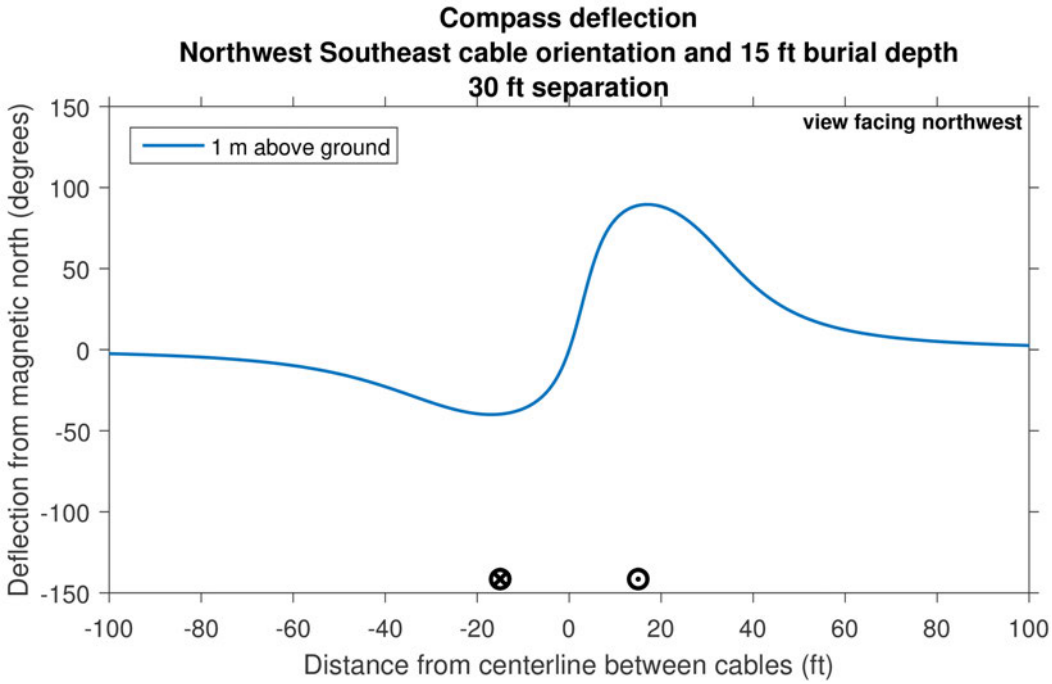

Figure 6. Compass deflection − Configuration 1a.

Compass deflection (degrees) from magnetic north 1 meter above ground for DC cables oriented northwest-southeast, buried 15 feet underground, separated by 30 feet, with northwestward current in the southwestern conductor.

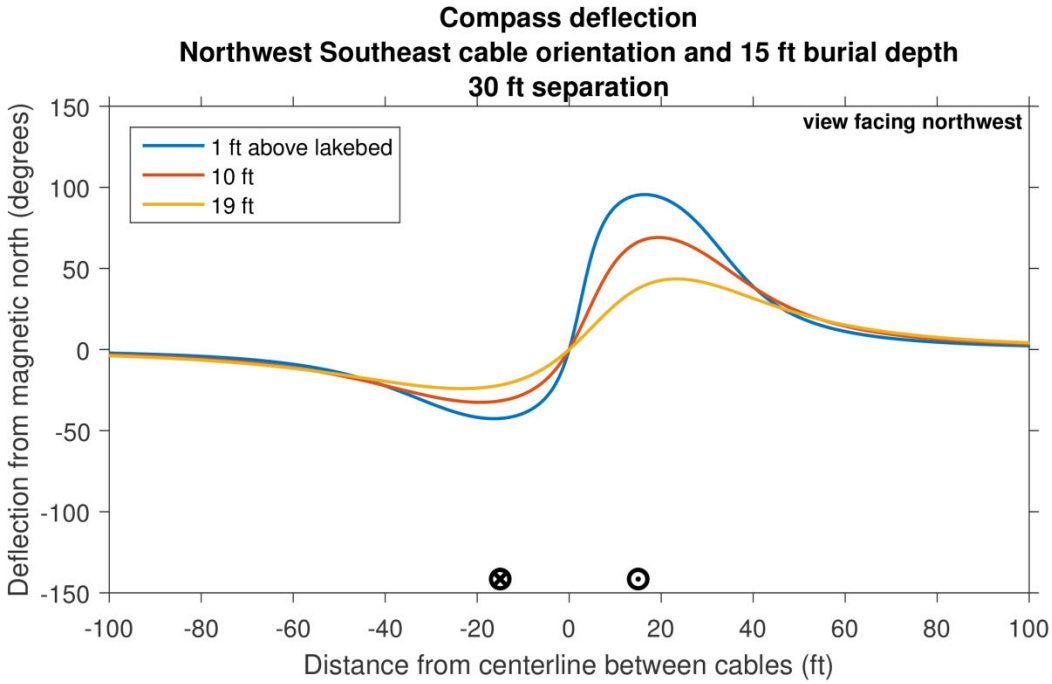

Figure 7. Compass deflection − Configuration 1b.

Compass deflection (degrees) from magnetic north for DC cables oriented northwest-southeast, buried 15 feet underwater, separated by 30 feet, with northwestward current in the southwestern conductor.

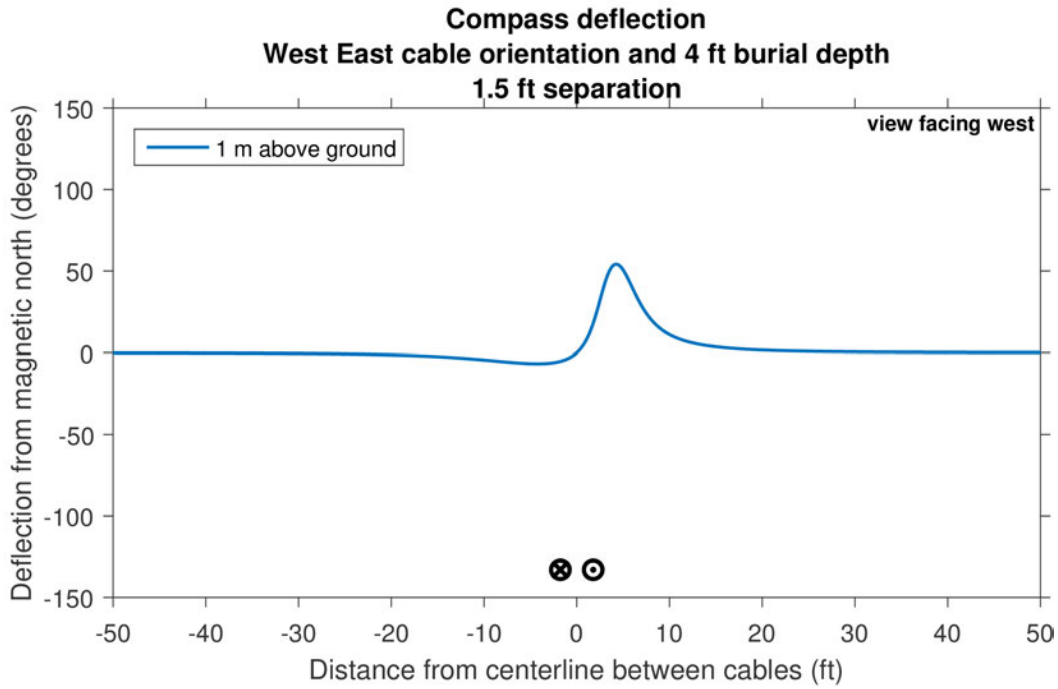

Figure 8. Compass deflection − Configuration 2.

Compass deflection (degrees) from magnetic north for DC cables oriented west-east, buried 4 feet underground, separated by 1.5 feet, with westward current in the southern conductor.

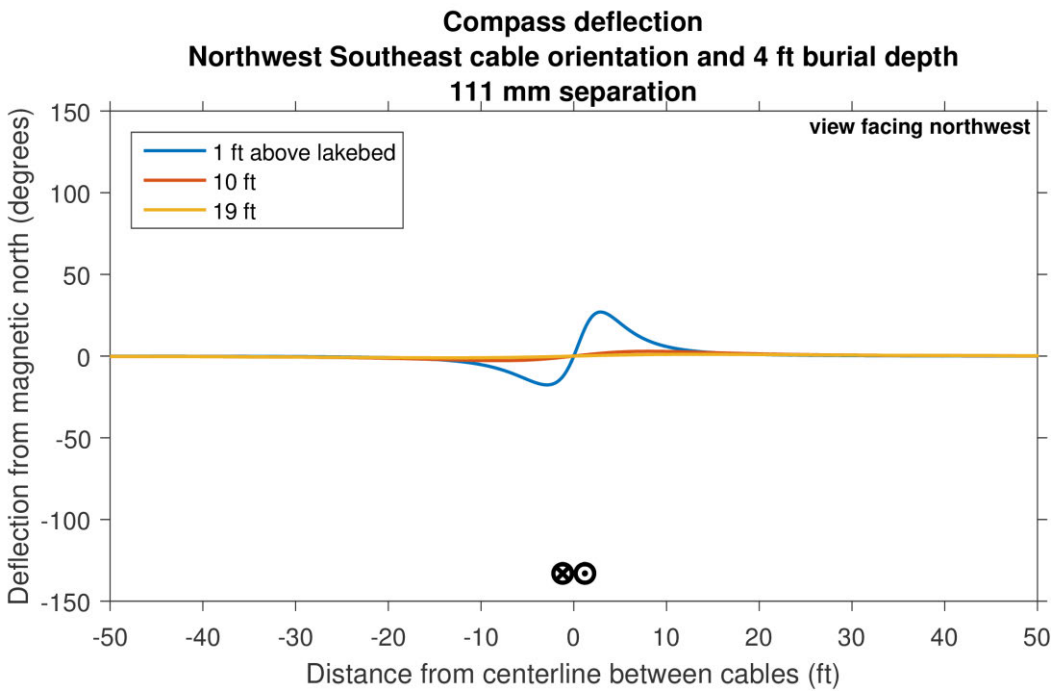

Figure 9. Compass deflection − Configuration 3.

Compass deflection (degrees) from magnetic north above the lakebed for DC cables oriented northwest-southeast, buried 4 feet underwater, separated by 111 mm, with northwestward current in the southwestern conductor.

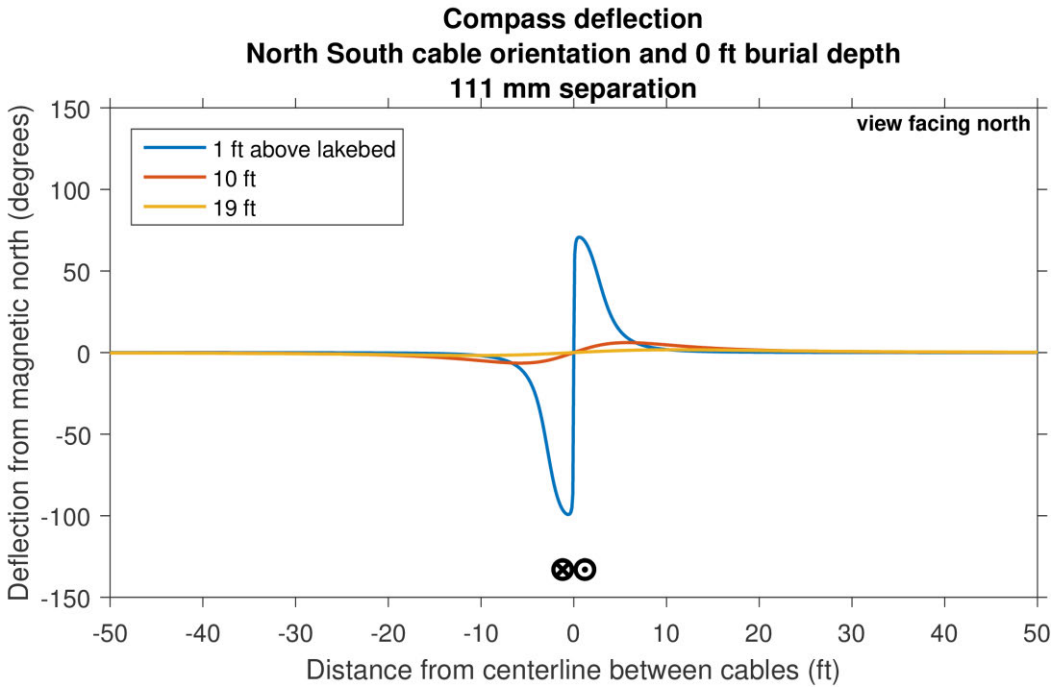

Figure 10. Compass deflection − Configuration 4.

Compass deflection (degrees) from magnetic north above the lakebed for DC cables oriented north-south, lying underwater on the surface of the lakebed, separated by 111 mm, with northward current in the western conductor.

Table 8. Configuration 1a − compass deflection (degrees) from magnetic north 1 meter above ground with DC cables in northwest-southeast orientation

	Distance from circuit centerline							
Cable burial depth and phasing	**-50 feet**	**-25 feet**	**-10 feet**	**Max + deviation**	**Max - deviation**	**+10 feet**	**+25 feet**	**+50 feet**
15 feet (northwestward current in the southwestern conductor)	-15	-37	-36	90	-40	80	81	21

Table 9. Configuration 1b − compass deflection (degrees) from magnetic north above lakebed with DC cables in northwest-southeast orientation

		Distance from circuit centerline							
Cable burial depth and phasing	**Height above lakebed (feet)**	**-50 feet**	**-25 feet**	**-10 feet**	**Max + deviation**	**Max - deviation**	**+10 feet**	**+25 feet**	**+50 feet**
15 feet (northwestward current in the southwestern conductor)	1	-14	-38	-39	96	-43	88	86	20
	10	-16	-31	-28	69	-33	54	66	23
	19	-15	-24	-18	44	-24	28	43	22

Table 10. Configuration 2 − compass deflection (degrees) from magnetic north 1 m above ground with DC cables in west-east orientation

	Distance from circuit centerline							
Cable burial depth and phasing	**-50 feet**	**-25 feet**	**-10 feet**	**Max + deviation**	**Max - deviation**	**+10 feet**	**+25 feet**	**+50 feet**
4 feet (westward current in the southern conductor)	-0.1	-0.8	-4.4	54	-6.7	11	0.9	0.1

Table 11. Configuration 3 − compass deflection (degrees) from magnetic north above lakebed with DC cables in northwest-southeast orientation

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
4 feet (northwestward current in the southwestern conductor)	1	-0.1	-0.5	-5.2	27	-18	5.8	0.5	0.1
	10	-0.2	-0.9	-2.7	2.9	-2.8	2.8	0.9	0.2
	19	-0.2	-0.7	-1.0	1.1	-1.0	1.0	0.8	0.2

Table 12. Configuration 4 − compass deflection (degrees) from magnetic north above lakebed with DC cables in north-south orientation

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
0 feet (northward current in the western conductor)	1	0.0	-0.1	-1.9	71	-99	1.9	0.1	0.0
	10	-0.1	-0.9	-5.0	6.1	-6.5	4.7	0.9	0.1
	19	-0.2	-1.0	-1.8	1.7	-1.8	1.7	0.9	0.2

Electric Field Induction

Water in Lake Champlain typically moves at a velocity of 4.8 cm/s (Manley et al., 1999). Fish and other animals in the lake will experience an induced electric field because of the motion of charges in the magnetic field. At this velocity, the induced electric field from the geomagnetic field alone will be very small, approximately 2.5 microvolts per meter (μV/m) or less.

In regions where the presence of underwater VGL cables (Configurations 1b, 3, and 4) alter the local ambient geomagnetic field, the induced electric field will be altered as well. Maximum values of the induced electric field experienced near the transmission line due to water velocity of 4.8 cm/s are tabulated in Table 13. In each configuration, the maximum electric field is calculated at 1 foot and 10 feet above the lakebed. The maximum induced electric field at a height of 1 foot above the lakebed is approximately 5.2 μV/m, 3.1 μV/m, and 17.7 μV/m for Configurations 1b, 3, and 4, respectively. At a height of 10 feet above the lakebed this induced electric field drops to 4.0 μV/m or less in all configurations. These values are in the range of the electric field induced in waters due to the ebb and flow of coastal tidal currents in the presence of earth's static geomagnetic field , 5-75 microvolts per meter (Normandeau et al., 2011).

Table 13. Maximum induced electric field 1 foot above lakebed for movement at a rate of 4.8 cm/s relative to the transmission line

Cable Configuration	Height above lakebed (feet)	Induced electric field (μV/m)
Configuration 1b	1	5.2
	10	4.0
Configuration 3	1	3.1
	10	2.6
Configuration 4	1	18
	10	2.7

Summary and Discussion

Magnetic Field

The total magnetic field (geomagnetic field + VGL cables) in the vicinity of the VGL cables is far below the ICNIRP standard for human exposure to static magnetic fields (< 0.1% of the general public exposure limit) for all configurations considered. Moreover, magnetic fields diminish rapidly with distance, so it is only in the immediate vicinity of the VGL cables that the magnetic-field level will be appreciably different than earth's geomagnetic field. The opportunity for human exposure to magnetic-field levels above that of the ambient geomagnetic field in Lake Champlain would be extremely limited and short term and therefore also not a problem for swimmers or boaters.

Configurations 1a and 1b – HDD

In the HDD configuration, the cables are proposed to be buried 15 feet underground or under the lakebed and separated by 30 feet. The magnetic-field level was calculated at a height of 1 meter above ground for Configuration 1a and at heights of 1 foot, 10 feet, and 19 feet above the lakebed for Configuration 1b. The magnetic-field levels in both Configurations 1a and 1b diminish relatively slowly with distance due to the large conductor separation in this configuration. The maximum total magnetic field on land where people might walk over the buried cables is 1,005 mG, less than ~0.1% of the ICNIRP standard for human exposure to static magnetic fields at all locations.

Configuration 2 – Upland Trench

Configuration 2 represents the upland trench portion of the route. The cables are buried 4 feet underground and separated by 1.5 feet. Despite the shallow burial depth, magnetic-field levels in this configuration are lower than for Configurations 1a or 1b and fall off with distance far more quickly due to the closer conductor spacing. At all locations above ground, the maximum

total magnetic field for Configuration 2 is 782 mG, less than ~0.1% of the ICNIRP standard for human exposure to static magnetic fields.

Configuration 3 – Jet Plow

Configuration 3 represents the underwater portion of the route in shallow areas (<150 feet deep), where the cables are proposed to be installed using a jet plow. The cables are proposed to be bundled together and buried 4 feet beneath the lakebed. Bundling the conductors together and burying them 4 feet beneath the lakebed results in the lowest total magnetic field compared to anywhere on the proposed route (a maximum total magnetic-field level of 661 mG). In this configuration, the decrease of the magnetic field with distance is so rapid as to be restricted primarily to a distance within approximately 10 feet on either side and above the cables.

Configuration 4 – Surface Laid

Configuration 4 represents the underwater portion of the route in deep water (>150 feet in water depth), where the cables are proposed to be bundled together and surface laid for the majority of the route (total length of approximately 35.6 miles). Configuration 4 has the highest total magnetic-field compared to the rest of the route since the cables are not buried (total magnetic field of 3,694 mG at the surface of the cables). Similar to Configuration 3, the conductors are bundled together, and so the magnetic field decreases with distance so rapidly that the magnetic-field deviation is largely restricted to a distance within approximately 10 feet on either side of and above the cables. At 10 feet on either side of the cable, the maximum change in the total field is just 30 mG.

Compass Deflection

Mariners use a compass to visualize the alignment of the horizontal component of the earth's geomagnetic field for navigation. 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. Modern navigational instruments that obtain compass readings

and locations from global positioning system receivers would not be affected by the VGL cables.

Configuration 1b is proposed over a distance of only <0.2 miles along the shore, an area where mariners are unlikely to require compass navigation. In Configuration 3, which is farther from land but still shallow water, a mariner in water depth of 10 feet would see a maximum deflection of less than 3 degrees even directly over the cable and at greater water depths the deviation would be even less. In regions where the cable is proposed to be laid on the lakebed, Lake Champlain is more than 150 feet deep and a mariner would see a maximum deflection of less than 1 degree. These compass deflections are too small to be likely to affect boaters' navigational decisions.

Electric Field Induction

The VGL cables are contained in metallic shielding, which shields the voltage thus blocking the electric field from reaching the marine environment. An induced electric field, however, is produced by the movement of electric charges in the ambient geomagnetic field or the total magnetic field (cable + ambient geomagnetic).

At a water velocity of 4.8 cm/s, the induced electric field from the ambient geomagnetic field alone is approximately 2.5 μV/m. With the presence of VGL cables, this induced electric field will increase near the cables. In Configurations 3 and 4, the induced electric field is 18 μV/m or less at 1 foot over the lakebed, and drops to 2.7 μV/m or less at a height of 10 feet over the lakebed. For Configuration 1b, the maximum induced electric field is 5.2 μV/m at 1 foot over the lakebed and drops to 4.0 μV/m at a height of 10 feet over the lakebed, but this configuration is proposed for only <0.2 miles along the shore. The effect of the induced electric field on marine life is discussed in detail in a following section.

AC Magnetic Fields

Calculations of the AC magnetic field for the ancillary underground transmission line between the New Haven Converter Station and the New Haven Substation were performed according the methods summarized in Appendix B and showed that the highest magnetic-field level above the

AC interconnection is 2% or less than the ICNIRP general public exposure limit for 60-Hz AC magnetic fields and below general standards for implanted medical devices, such as the European Committee for Electrotechnical Standardization's EN 50527-1 Standard, which specifies that the function of implanted medical devices should not be impaired at AC magnetic-field levels below 100 μT (1,000 mG).[8]

AC Magnetic Fields

Calculations of the AC magnetic field for the ancillary underground transmission line between the converter station and the New Haven Substation in New Haven, Vermont were performed according the methods summarized in Appendix B and showed that the AC magnetic-field levels (20 mG or less at the ROW edge, at approximately 1 meter (3.28 feet) above ground level) are less than 2.5% of ICNIRP guidelines for the general public. These levels are also far below general standards for implanted medical devices, such as the European Committee for Electrotechnical Standardization's EN 50527-1 Standard as well as ANSI/AAMI/ISO 14117:2012, both of which reference ICNIRP 1998 limits and specifies that the function of implanted medical devices should not be impaired at 60-Hz AC magnetic-field levels below 83.3 μT (833 mG).[9]

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[8] European Committee for Electrotechnical Standardization (CENELEC). Procedure for the assessment of the exposure to electromagnetic fields of workers bearing active implantable medical devices - Part 1: General Std. EN 50527-1, April, 2010

[9] European Committee for Electrotechnical Standardization (CENELEC). Procedure for the assessment of the exposure to electromagnetic fields of workers bearing active implantable medical devices - Part 1: General Std. EN 50527-1, April, 2010

Fish Species of Interest

Exponent's analysis has focused on certain species of interest, which were selected utilizing two criteria. First, species listed as high priority for conservation efforts by the Vermont Department of Fish and Wildlife (VDFW, 2015) and are documented to reside in Lake Champlain have been included for review. These fish include lake sturgeon (*Acipenser fulvescens*), silver lamprey (*Ichthyomyzon unicuspis*), blackchin shiner (*Notropis heterodon*), bridle shiner (*Notropis bifrenatus*), greater redhorse (*Moxostoma valenciennesi*) and sauger (*Sander canadensis*). Second, resident Lake Champlain fish species listed as medium conservation priority were also included if they had documented responses to magnetic-field alterations. These include American eel (*Anguilla rostrata*) and the salmonids Atlantic salmon (*Salmo salar*) and lake trout (*Salvelinus namaycush*). Utilizing these two criteria to select species for review ensures that both those taxa that could be considered sensitive due to pre-existing population declines and taxa with documented ability to detect altered magnetic fields are considered in this analysis. This section summarizes the life history and ecology of the four fish species of interest, and provides a review of the relevant literature pertaining to the effects of exposure to static magnetic fields on freshwater fish species to assess the potential for adverse effects on high priority fish species in Lake Champlain.

Lake Sturgeon

The lake sturgeon is a large, long-lived freshwater member of family *Acipenseridae* that was listed as a State of Vermont endangered species in 1975 (VDFW, 2015). The Lake Champlain basin is currently the only state waterbody that contains lake sturgeon. This species is potamodromous (i.e., migrating within freshwater systems to spawning sites, usually from a larger lake system into tributaries) and exhibits strong spawning site fidelity (Bemis and Kynard, 1997). Adult lake sturgeon are omnivorous benthic feeders, sucking up prey items in mud, sand, or gravel substrates at about a depth of 5 to 9 meters (fishbase.org). This species is noted for its exceptionally long lifespan. Age at first spawning ranges from 15 to 20 years of age, and individual life span might be 80 years or more (PNHP, 2014b). Because of this slow growth, population recovery following overfishing, habitat degradation, and dam construction is

expected to be slow (VDFW, 2015). Dam construction on the Missisquoi and Lamoille Rivers has limited access to suitable spawning areas reducing the viability of the Lake Champlain sturgeon population (VDFW, 2015). In the absence of barriers, however, nonanadromous sturgeon can swim 100-plus kilometers (Nature Serve, 2016a).

Silver Lamprey

Silver lampreys are elongate fishes with disc-shaped sucking mouths. Juveniles burrow into the soft substrates of streams and rivers, before transitioning to large tributaries and lakes as adults (COSEWIC, 2011). Like invasive sea lamprey (*Petromyzon marinus*), silver lamprey are parasitic. Adults attach themselves to host fish via their sucking disc mouth and feed on host fish blood and tissue. Prior to spawning, adult detach from the host fish and move to the riffle sections of rivers and streams (COSEWIC, 2011). Silver lamprey are broadly distributed throughout Lake Champlain and its tributaries in Vermont (VDFW, 2015), where they parasitize host fish including lake sturgeon, northern pike (*Esox lucius*), and white sucker (*Catostomus commersonii*) (MDNR, 2016). Currently, the Lake Champlain silver lamprey population is threated by habitat degradation, barriers to spawning grounds, and programs enacted to control invasive sea lamprey in Lake Champlain (VDWF, 2015). Although this species is broadly distributed across the Great Lakes region, it is declining in Lake Champlain. Silver lamprey populations separated by distance of 10 km or more or by insurmountable barriers such as dams or high waterfalls are considered independent populations (Nature Serve, 2016b).

Blackchin and Bridle Shiners

Eastern shiners (genus *Notropis*), including blackchin and bridle shiners, are small, silvery, minnow-like fish that inhabit clear waters over sandy substrate in lakes and streams. These small fish represent a significant forage fish population for large predatory fish, including recreationally-fished species. Bridle shiner populations have been declining in the eastern United States and Canada (Boucher et al., 2011). Less is known about the status of the blackchin shiner in the Great Lakes region, but this species has been extirpated from a number of New York watersheds. Water quality degradation has attributed for much of the bridle shiner's decline across its range (VDFW 2015), and has likely impacted blackchin shiner

populations as well. Both species prefer vegetated edges for spawning, and loss of this habitat may also constitute a threat to blackchin and bridle shiner populations (VDFW, 2015). Data from Nature Serve indicate that these shiners are non-migratory, and fish located within 10 km are considered a single population if sufficient pockets of habitat exist along the route (Nature Serve, 2016c). Nature Serve data also suggest that bridle shiner are more at risk than blackchin shiner, which is noted to be "represented by a large number of subpopulations and locations."

Greater Redhorse

The greater redhorse is a long-lived highly migratory fish species that inhabits large interconnected river and lake basins. Adults feed on benthic invertebrates and lake populations spawn in shallow portions of the lake or move into large tributaries (Healy, 2002). In Lake Champlain, this fish species has been recorded as inhabiting the northern portion of the lake, though it is rarely collected (VDFW, 2015). The life history of the greater redhorse, including traits such as delayed maturation, longevity, and seasonal spawning based on environmental cues (i.e., changing temperatures and increased tributary flow), may increase population sensitivity to external threats (USDA, 2002). In the Lake Champlain basin, poor water quality, habitat fragmentation, and altered water flow present the greatest threats to the resident greater redhorse population. Data made available by Nature Serve indicates that greater redhorse do migrate sometime considerable distances between spawning and non-spawning habitats; however, populations separated by a gap of 20 km or more (or barriers such as a dam or high waterfall) are considered independent populations (Nature Serve, 2016d).

Sauger

Sauger are a large fish, in the same genus as walleye (*Sander vitreus*), and are thus sought after by anglers (River Keepers, 2011). Once widely distributed across its range, saugers have been extirpated from New York outside of Lake Champlain. The only population of saugers within the state of Vermont inhabits Lake Champlain, although these fish are rarely captured and seem to preferentially inhabit the southern end of the lake (VDFW, 2015). Saugers are predatory fish that are found in turbid areas of lakes, feeding in the evenings or at night (MNFI, 2004). Adults spawn over gravel and cobble shoals in the tributaries of lakes (MNFI, 2004). Saugers are a

highly migratory fish, undertaking migrations of hundreds of kilometers in length. However, this requires wide access to multiple interconnected habitats, and as such, this species is very sensitive to habitat alterations that would restrict migrations, such as dam construction (VDFW, 2015). This species is also very sensitive to changes in water quality, especially the loss of turbid water habitats. Information from Nature Serve on saugers' population separation differences is limited, but despite the migratory status of this species, individuals more than 10 km apart are considered to represent independent populations (Nature Serve, 2016e).

American Eel

American eels (*Anguilla rostrata*) are a catadromous species that inhabit Lake Champlain for the adult portion of their life cycle. The American eel is a commercially and recreationally harvested fish through much of its range (Facey and Van Den Avyle, 1987). Spawning and early development occurs in oceanic waters and the juvenile eels move into freshwater areas to complete growth; the reproductively immature eels may inhabit inland lakes and rivers for years prior to the first spawning trip to oceanic waters (Facey and Van Den Avyle, 1987). The Richelieu River is the primary migration route for American eel inhabiting Lake Champlain, but populations declined in the late 1990s due in part to the rebuilding of two dams on this river (Staats, 2014). Efforts to improve this population include construction of eel ladders at the dam sites and implementation of an eel stocking program by the government of Quebec (Staats, 2014). Recent sampling indicates that while recruitment has improved somewhat, it is still "far from what seems necessary to rebuild the eel stock in Lake Champlain" (Staats, 2014). The VDWF reports that American eel are rarely encountered in the Vermont portion of Lake Champlain (VDFW, 2015). This species is broadly distributed throughout much of the eastern United States, and given that American eels have been known to travel thousands of kilometers between ocean spawning habitats and in-land areas, all individuals downstream from the inland-most occurrence can be considered part of the same population (Nature Serve, 2016f).

Salmonids: Lake Trout and Atlantic Salmon

Species in the family Salmonidae include salmon, trout and char, and are generally characterized by a large body size. Key salmonid that inhabit the Lake Champlain system include Atlantic salmon and lake trout. According to the VDFW, it is unclear whether Atlantic salmon are endemic to Lake Champlain, given the high stocking rates of this fish (VDFW 2015). Similarly, the Lake Champlain population of wild lake trout was extirpated, and a stocking program instituted to re-establish the species. It should be noted that an active stocking program likely increases the population viability of this fish. Atlantic salmon utilize cool streams for spawning and juvenile habitat, and adults inhabit oligotrophic lake waters when not spawning; conversely, lake trout remain within the lake, spawning along rocky shorelines (VDFW 2015). The Lake Champlain populations of both species are landlocked and non-anadromous, and have population separation distances of approximately 10 to 60 km (Nature Serve 2016g,h).

Effects of Static Magnetic Fields on Freshwater Fish

Many and diverse species of fish, including salmonids, tuna, herrings, carp, and mackerel, contain particles of magnetite, the most magnetic of all naturally-occurring minerals on earth (Harrison et al., 2002), within their skeletal systems. The presence of these particles in association with sensory nerves is thought to help fish detect the earth's geomagnetic field, allowing for it to be used as an external cue to orient and guide migrations (Hanson and Westerberg, 1987; Walker et al., 1998; Öhman et al., 2007; Tanski et al., 2011). This ability appears especially valuable to those fish that undergo extensive migrations, including some salmonid species (Quinn, 1980; Quinn and Brannon, 1982) and sturgeon (Cada et al., 2011).

The movement of fish and other aquatic species through a static magnetic field results in the production of an induced electric field that can be detected by some freshwater species (Normandeau et al., 2011). Sturgeon are particularly sensitive to magnetic fields and electric field induction due the presence of sensitive electroreceptors called *ampullae of Lorenzini* on the snout and gills; these allow these fish to detect electric field gradients down to 500 microvolts per meter (µV/m) (Bouyoucos et al., 2013) ; these are thought to be used in the detection of prey. Lamprey have similar electroreceptors distributed broadly in their skin and over the full length of their body, in addition to the head (Bodznick and Preston, 1983); it has been theorized that these are used to help in location of conspecifics over short distances (Chung-Davidson et al. 2008). As such, lamprey may be as sensitive to magnetic fields and induced electric fields as sturgeon.

Evidence from the literature indicates that certain fish species, to varying degrees, are capable of detecting and responding to magnetic fields or in some cases electric fields induced by movement in the earth's static geomagnetic field. The possibility that alterations in the static magnetic field around the Project's cables could potentially affect fish behavior or physiology deserves consideration. Therefore, a review of the pertinent literature on the effects of static magnetic fields on freshwater aquatic life, including those on early fish life stages, behavior, migration and physiology is provided below.

Potential effects of static magnetic fields on larval fish

The vast majority of bony fish exhibit external fertilization, where gametes are released into the water, which results in the production a large number of small eggs. These eggs, along with young larvae, are passively dispersed throughout the water body via currents; later life stages gain the ability to swim and direct movement.

Physiology

The inconsistent results of a number of laboratory studies provide no clear conclusion as to effects of exposure to high intensity static magnetic fields on fish eggs and larvae. Exposure to a static magnetic field of 2 mT (20 G) resulted in increased permeability of the eggs of three different salmonid species, including Atlantic trout (Sadowski et al., 2007). However, it is unclear what quantitative effect this might have on egg survival and development. Woodruff et al. (2012) examined the effects of a maximum 3mT (30 G) magnetic field on the fertilization, hatching rates, and development of the eggs of the rainbow trout (*Oncorhynchus mykiss),* and found no significant effects of magnetic field exposure on fertilization success or hatch rates. Time to hatch was similarly unaffected (Woodruff et al., 2012). Conversely, exposure to 1 and 13 mT (10-130 G) magnetic fields prolonged embryonic development of O. *mykiss* and brown trout (*Salmo trutta*) eggs (Formicki and Winnicki, 1998). Larval weights also were significantly increased by exposure to the magnetic field, but exposed fish larvae were also more mobile than controls.

In addition to effects on fertilization and early life stages, the effects of magnetic fields on aspects of fish physiology or homeostasis have also been studied. Laboratory exposure to a 40 µT (400 milligauss [mG]) magnetic field with a frequency of 1 Hz produced by current pulses of 200 milliseconds [ms] on and 800 ms off) increased nocturnal melatonin levels in adult brook trout (*Salvelinus fontinalis*; Lerchl et al. 1998). Melatonin is a hormone that structures fish sleep/wake cycles and other seasonal physiological rhythms. These authors theorized that the magnetic field either stimulated the pineal gland, which caused a release of melatonin, or that exposure to the altered magnetic field resulted in a stress response cascade that led to a release of melatonin (Lerchl et al., 1998). However, the potential implications on trout health and

population fitness were not addressed. Further, because the magnetic field was pulsed, it is likely that the observed responses were a result of oscillating electric fields induced in the fish when the field was modulated, an exposure scenario that is different from the constant magnetic field that would be produced by Vermont Green Line Project cables. To that point, Woodruff et al. (2012) examined the effects of 0.1 mT to 3 mT (i.e., 1 to 30 G) static magnetic fields on hormonal indicators of stress in coho salmon (*Oncorhynchus kisutch*). Plasma cortisol levels in exposed fish were unaffected by 80h exposures to magnetic fields, while melatonin levels in coho were reduced by exposure to the 3.0 mT (30 G) strength field, but were unaffected by 0.1 mT (1 G) field exposures (Woodruff et al. 2012). Woodruff et al. concluded that there was no evidence that magnetic fields elicited a stress response in exposed fish.

Behavioral Responses

Exposure to extremely high magnetic fields has been shown to disrupt the physiological homeostasis of some early life stage fish. Carp (*Cyprinus carpio*) and pike (*Esox lucius*) embryos and larvae responded to a constant 50 to 70 mT (500-700 G) magnetic fields with a 5% increase in heartrate (Formicki and Winnicki, 1996; Winnicki et al., 1993). The effects were transitory, however, as heart rates returned to normal when embryos and larvae were moved from the magnetic field. Further, weaker fields were found to have no effect on heart rates (Formicki and Winnicki, 1996; Winnicki et al., 1993). Formicki et al. (1992) documented increased pectoral fin movement during exposure of brown trout larvae to stable 50 to 70 mT (500-700 G) magnetic fields. Older free-swimming salmonid larvae and fry were also observed to exhibit behavioral response to elevated magnetic fields. Young fish showed a positive swim response toward a static magnetic field of 4.2 mT (42 G), with older fish demonstrating a more pronounced response (Formicki et al., 2004). According to researchers, this response may have been an “investigative response” behavior triggered by the altered magnetic field.

Potential effects of static magnetic field on adult and juvenile fish

For mobile adult and juvenile fish, exposure to altered magnetic fields can affect a number of behaviors. However, as with the studies conducted with embryonic and larval fish, many

documented effects occur following exposure to very strong magnetic fields within laboratory settings. Yet, understanding the nature of fish responses toward altered magnetic fields will assist in predicting the likelihood of population-level effects from the Vermont Green Line Project.

Exposure of fathead minnows, *Pimephales promelas*, to a static magnetic field of 36.4 millitesla (mT)[10] (equivalent to 364 Gauss [G] or 364,000 mG) resulted in no evidence of either attraction or avoidance of the metal bar providing the magnetic field (Cada et al., 2011). Additional studies were conducted in the same laboratory using lake sturgeon (*A. fulvescens*), striped bass (*Morone saxatilis*), channel catfish (*Ictalurus punctatus*), and fathead minnows; results of these studies again indicated that the presence of the 36.4 mT static magnetic field did not affect the distribution of these fish in the tank. However, over a 46-hour testing period, the movement of fathead minnows was increased in the presence of the elevated magnetic field (Cada et al., 2012). Lake sturgeon, striped bass and channel catfish did not exhibit significant changes in swim speed or movement. Based on the findings of these two studies with four fish species, the authors concluded that the "results suggest that the predicted EMF [static magnetic field] that may be created by a single submerged DC [direct current] transmission cable from an HK [hydrokinetic] project would not seriously affect the behavior of common freshwater species" (Cada et al.2012, p. 25).

In a separate series of laboratory experiments conducted at the same facility, a number of freshwater fish species (fathead minnow, *P. promelas*, redear sunfish, *Lepomis microlophus*, striped bass, *M. saxatilis*, lake sturgeon *A. fulvescens*, and channel catfish *I. punctatus*) were exposed to a static magnetic field (36.4 mT or 364 G) generated by a permanent magnet (Bevelhimer et al. 2013). As with previous studies, the magnetic field did not affect the distribution of striped bass, lake sturgeon, or fathead minnow in the aquarium. However, redear sunfish and channel catfish were more likely to congregate over the magnets (Bevelhimer et al. 2013).

[10] Tesla is another unit to express magnetic flux density. For purposes of comparison 1 microtesla (µT) equates to0.01 Gauss or 10 milligauss (mG). 1 millitesla equates to 10 Gauss, or 10,000 milligauss (mG)

Given the number of key Lake Champlain fish species that undergo migrations and the importance of this behavior in sustaining populations, the potential effects of the magnetic field proposed DC cable on these behaviors is also addressed. As summarized earlier, many fish species utilize geomagnetic cues, in additional to olfactory, visual and other environmental cues, to guide migration. The most comprehensive field study on the effect of DC cables on fish migrations examined the migratory behavior of marine eels (*Anguilla anguilla*) near DC cables in the Baltic Sea (Westerberg and Begout-Anras, 2000). Although conducted with a different species, findings are likely relevant to the closely related species, the American eel (one of the species of interest in Lake Champlain). The Baltic HVDC cable system produced a magnetic field of 5 microtesla (µT) (50 mG) at a distance of 60 meters from the cable; the movement of tagged eels was unaffected by the cable's presence. Hence, authors concluded that there was no evidence that the migratory behavior of tagged eels was affected by the magnetic field produced by the DC cable, and therefore, it "was unlikely to be an obstacle that could influence the escapement of eels" (Westerberg and Begout-Anras, 2000, p. 154). Although similar studies have not been conducted with other migratory species of interest (salmonids and lake sturgeon), it can be inferred from this study that, under field conditions, effects from DC cables are likely to be minor and transitory, especially given that the Project will affect a very small portion of available eel habitat.

Like eels, Atlantic salmon and other related salmonid species can undergo significant migrations. Laboratory experiments have indicated that migratory salmonids can use static magnetic fields to guide movement in the absence of ambient light (Hellinger and Hoffman, 2012). In general, static magnetic cues in conjunction with olfactory and visual cues appear to support both long-range migration and short-range movements. However, in a study of the relative importance of various migration cues, inland-spawning salmonids reportedly responded better to olfactory cues than offshore-spawning species (Putman et al., 2014a). This observation also was reported by Dittman and Quinn (1996), who state that olfactory cues are the primary cue governing freshwater migrations. Exposure to altered magnetic fields (intensities between 42 and 55 µT [0.42 to 0.52 G] with an inclination angle ranging from 62.68° to 70.78°) for multiple months caused young steelhead trout not to orient to the natural magnetic field (Putman et al., 2014 b). However, an exposure of this duration is not expected with the Vermont Green

Line Project, and it should be noted that authors found no similar effect following transitory exposures to altered magnetic fields. Further, salmonids have been observed to regain orienting abilities once removed from the area with an altered magnetic field (Taylor, 1986).

Potential effects of induced electric fields

Multiple fish species, including the salmonids *Oncorhynchus keta* and *Salvelinus alpinus* have been shown to generate a weak static electric field while swimming through the water; in freshwater systems, fish produced static electric fields up to 25,000 µV/cm (Butsuk and Bessnov, 1981), far greater than the strength of electric fields induced by movement of fish, large invertebrates, or other objects through the geomagnetic field including that around the proposed DC cables. Both lampreys and sturgeon have means to detect such signals. Lampreys are reported to respond to weak electrical fields in the range of 0.1 to 20 µV/cm (Normandeau et al., 2011). However, responses to these weak electrical fields reportedly differ over the life cycle of the lamprey. Parasitic-stage sea lamprey (*P. marinus*) swam constantly when exposed to electric fields ranging between 1 and 30 µV/cm (Chung-Davidson and Yun 2004); yet, adult stage sea lamprey were largely inactive when stimulated with electric fields of the same magnitude (Chung-Davidson et al., 2008). Similarly, Atlantic sturgeon (*Acipenser oxyrhynchus*) have been reported to respond to electric fields in the as low as 5 µV/cm (Bouyoucos et al 2011). This electrosensory ability is thought to help with the detection of benthic prey (Peterson et al., 2007). When juvenile lake sturgeon were exposed to an AC-produced magnetic field of 165 mT (1,560 G), fish exhibited a temporary alteration in swimming behavior; however, this may have been in response to the sudden appearance of the AC-power-generated magnetic field (Cada et al., 2012). Although swimming behaviors were altered, there was little evidence of avoidance of the AC magnetic field by juvenile sturgeon. Other sturgeon species have been demonstrated to respond to both weak DC and low frequency AC electric signals (Gill et al., 2012). Lake sturgeon, however, are reported to utilize multiple means of detecting benthic prey, including olfactory, tactile, and chemosensory cues, in addition to relying on electric signals from prey movement (Peterson et al., 2007). For instance, sturgeons are able to detect prey *via* taste bud-covered barbels that they drag through the sediment (Boglione et al., 1999), and although Siberian sturgeon (*Acipenser baerii*) exhibited feeding behaviors in response to an aluminum pole with a peak-to-peak signal of 90 microvolts

(µV), similar behaviors were also induced though olfactory stimulation alone (Zhang et al., 2012). A lower electric signal of 15 µV had no effect on sturgeon feeding behavior.

The induced electric field from the Project was calculated to be elevated for about 1 foot above the lakebed over the Project cable; background magnetic fields are predicted at about 10 ft (3 m) above the lakebed over the Project cable (Case 4). For a fish swimming at 4.8 cm/s per second the maximum induced electric field is18 µV/m at 1 ft and 4.0 µV/m or less at 10 ft. The reported detection threshold for Atlantic sturgeon is 500 µV/m (Bouyoucos et al., 2013) and 100 µV/m for lampreys (Normandeau et al., 2011) so it is not likely that prey or host detection by electro-sensitive sturgeon and lamprey would be affected by the magnetic field via induction of electric fields in the vicinity of the Project.

Assessment and Discussion

Although exposure to static magnetic fields has been demonstrated to result in altered fish behavior and physiology in some laboratory studies, these effects were documented following exposure to much stronger magnetic fields than would be expected to occur due to the Vermont Green Line Project. Observed responses of fish to static magnetic fields from laboratory studies (e.g., increased movement, variations in swimming behavior, attraction) are not clearly harmful to fish health and fitness, and further, these effects typically reverse as the fish leaves the area of increased static magnetic field (Formicki and Winnicki, 1996, Bevelhimer et al., 2013).

The calculations of static magnetic field strength around the buried Vermont Green Line Project DC cable indicate that the maximum expected field strength is 3,694 mG Configuration 4) at a distance of 1 ft above the cable; ambient geomagnetic field is achieved at an approximate distance of 10 ft above seabed. A summary of studies reviewed above is presented in Tables 14 and 15, and it should be noted that the majority of these studies examined the effects of magnetic fields much greater than those calculated to occur at the Vermont Green Line Project Site (maximum 3.7 G). Many of these studies found no significant effects on fish at these high exposure levels. In fact, only Lerchl et al. (1998) reported a significant physiological response following exposure to an intermittent pulsed AC magnetic field with a frequency of 1 Hz at a strength similar to the highest value for the proposed Project at the surface of unburied cables.

However, it is unclear if this effect would occur in a static field as opposed to the pulsed AC field tested by Lerchl et al. (1998) or if increased melatonin levels in fish would cause adverse health effects.

Given that the magnetic field strengths in the majority of the studies summarized above are much higher than that calculated around the DC cable and the responses to the field are reported more frequently at higher exposures suggestive of a dose-response relationship, the effects reported in the literature are not expected to occur under field conditions in Lake Champlain. Hence, we conclude that the static magnetic field generated during Project operations is unlikely to result in any significant impact on individual-level fitness or effects at the population-level for resident fish species.

Since the effects of altered magnetic and/or induced electric fields have been tested in salmonids, lamprey, eel, and sturgeon species, we can conclude that assessment of these effects provide a reasonable estimation of the likely sensitivities of the following key species of interest in Lake Champlain: lake sturgeon, Atlantic salmon, lake trout, silver lamprey, and American eel. Conversely, the ability of greater redhorse, sauger, blackchin shiner, and bridle shiner to detect altered magnetic fields is unknown. Although this comprises an uncertainty within this assessment, it can be reasonably assumed that the ability of these species to detect altered static magnetic fields is similar to that of the wide range of species reviewed herein. Further, the area of Lake Champlain fish habitat where the geomagnetic field is altered by the underwater cable is very small in comparison to the likely total area utilized by each of the fish species of interest. According to data from Nature Serve, a single independent population of fish can inhabit all suitable habitats within a multiple kilometer radius (for some species as much as hundreds or thousands of kilometers); for each of these identified Lake Champlain fish species, all suitable habitats within at least 10 km will likely support a single interconnected population of fish (NatureServe, 2016a-h). For example, cables generating an increased magnetic field over a 3-meter radius over most of the proposed Project cable route would affect less than 0.1% of the minimum population range (i.e., 6 meters affected over 10,000 meters of shoreline or shallow water habitat). Consequently, given the small proportion of habitat projected to be associated with a change in the magnetic field from the Project cable, along with the minor and generally

reversible nature of documented effects of static magnetic fields on freshwater fish, it is unlikely that the static magnetic field from the buried cable will constitute any significant threat to resident fish populations in Lake Champlain, including fish species listed as high priority by the State of Vermont.

Table 14. Summary of studies of larval freshwater fish exposed to high intensity static magnetic fields

Study	Species Relevant to Project Area	Magnetic Field	Response
Physiology			
Lerchl et al., 1998	Brook trout	0.04 mT (0.4 G)	Increased melatonin levels
Woodruff et al. (2012)	Coho salmon	0.1 – 3 mT (1-30 G)	No effect on stress response (cortisol) with 80 hour exposure. Melatonin levels reduced by 3 mT.
Formicki and Winnicki, 1998	Rainbow trout Brown trout	1 - 13 mT (10-130 G)	Prolonged embryonic development, increased larval weight & mobility
Sadowski et al. 2007	Atlantic trout	2 mT (20 G)	Increased egg permeability
Woodruff et al. (2012)	Rainbow trout	3mT (30 G)	No effect on fertilization, hatching rates, and development of the eggs
Formicki et al., (2015)	Brown trout	1 mT (10 G), 5 mT (50 G), 10 mT (100 G)	Prolonged sperm motility, increased fertilization rate
Behavioral responses			
Formicki et al., 2004	Salmon	4.2 mT (42 G)	Positive investigative response by fry, enhanced in older fish
Formicki and Winnicki, 1996; Winnicki et al., 1993	Carp, Pike	< 50 - 70 mT (500-700 G)	No effect
		≥ 50 - 70 mT (500-700 G)	5% increase in heartrate during exposure
Formicki et al. (1992	Brown trout	50 -70 mT (500-700 G)	Increase pectoral fin movement

Table 15. Summary of behavioral studies of juvenile and adult freshwater fish exposed to high intensity static magnetic fields

Study	Species Relevant to Project Area	Magnetic Field	Response
Westerberg and Begout-Anras, 2000	Eels	5 µT (50 mG)	No effect on migratory behavior of tagged eels crossing DC cable
Hellinger and Hoffman, 2012	Rainbow trout	30 µT (300 mG)	After 5-19 days of training, discrimination of increase in field or 90° shift observed
Putman et al. 2014 b	Steelhead trout	42 - 55 µT (0.42 -0.52 G)	Orientation to dipole field varied with polarity of magnetic field
Woodruff et al., 2012	Coho salmon	0.1-3 mT (1-30 G)	No effect on stress response (cortisol) with 80 hour exposure. Melatonin levels reduced by 3 mT.
Bevelhimer et al. 2013		36.4 mT (364 G)	No behavioral response
	Fathead minnow, striped bass, lake sturgeon, Redear sunfish, channel catfish	36.4 mT (364 G)	Increased time spent over magnet
Cada et al., 2011	Fathead minnows	36.4 mT (364 G)	No behavioral response
Cada et al., 2012	Lake sturgeon, striped bass, channel catfish, fathead minnows	36.4 mT (364 G)	No behavioral response Increased movement of fathead minnows after 48 hours
Taylor, 1986	Salmon	Ambient geomagnetic field with altered horizontal component	Change of 90° in horizontal component shifted preferred orientation after 3 days of exposure

Conclusions

1) The calculated total static magnetic field (cable plus ambient geomagnetic) in the vicinity of the VGL cables on land is far below the ICNIRP standard for human exposure to static magnetic fields (< 0.1% of the general public exposure limit) for all configurations considered. Similarly, the AC magnetic field associated with very short underground cables is about 2% or less than limits on human exposure of the public recommended in international standards.
2) Small deviations in boaters' compass readings but not GPS receiver readings are projected, but would be very small (< 3 degrees) and only encountered in a small zone within about 25 feet of the cables in areas of Lake Champlain where compasses would be relied upon.
3) Based on a review of the relevant scientific literature, the change in the background geomagnetic field produced by the VGL DC cables in Lake Champlain would not cause adverse impacts on resident populations of aquatic fish species. This assessment indicates that:

    a. The potential for adverse effects of altered static magnetic or induced electric fields is quite low or non-existent;

    b. 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 changes in the geomagnetic field; and

    c. Orientation and migratory behaviors result from an integration of multiple cues. For the underwater portion of the route most of the cable will be laid in deep water where fish populations are sparse. At these depths, the maximum magnetic field will be highest within ± 1 foot of the cable but at 10 ft, will be of the same order of magnitude as cables buried 4 feet or more in shallower water except for a short distance where the cable will be in an HDD configuration. Where the cables self-bury (which Vermont Green Line

Devco estimates will occur to a depth of approximately 1 foot), the change in the magnetic field will be less.

d. For a smaller portion of the underwater route the cable will be jet plowed beneath the lakebed in waters with depths less than 150 ft where fish are most prevalent. Here, the resulting change in the maximum magnetic field will be very small (125 mG) even directly over the cable. Further, calculations at maximum load on the VGL cable show that the area most affected by the VGL cable (~10 ft 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.

e. Only two species of concern in the lake are known to have specialized electric field sensory organs. The range of detection for induced electric fields reported in the literature (as may be induced by fish movement) is small, less than 20 inches in most configurations, and the area of increased induced electric field is unlikely to extend around the VGL cables beyond 10 ft where magnetic fields and induced electric fields approach background levels.

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Limitations

At the request of TRC Solutions on behalf of its client, Vermont Green Line Devco, LLC, Exponent calculated the magnetic-field levels for a proposed ±150-kV DC transmission line in Lake Champlain with the capacity to carry 409 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 TRC Solutions and its consultants with respect to parameters and configurations of the transmission line. Vermont Green Line Devco, LLC, has confirmed to Exponent that the data contained herein are not subject to Critical Energy Infrastructure Information restrictions. 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

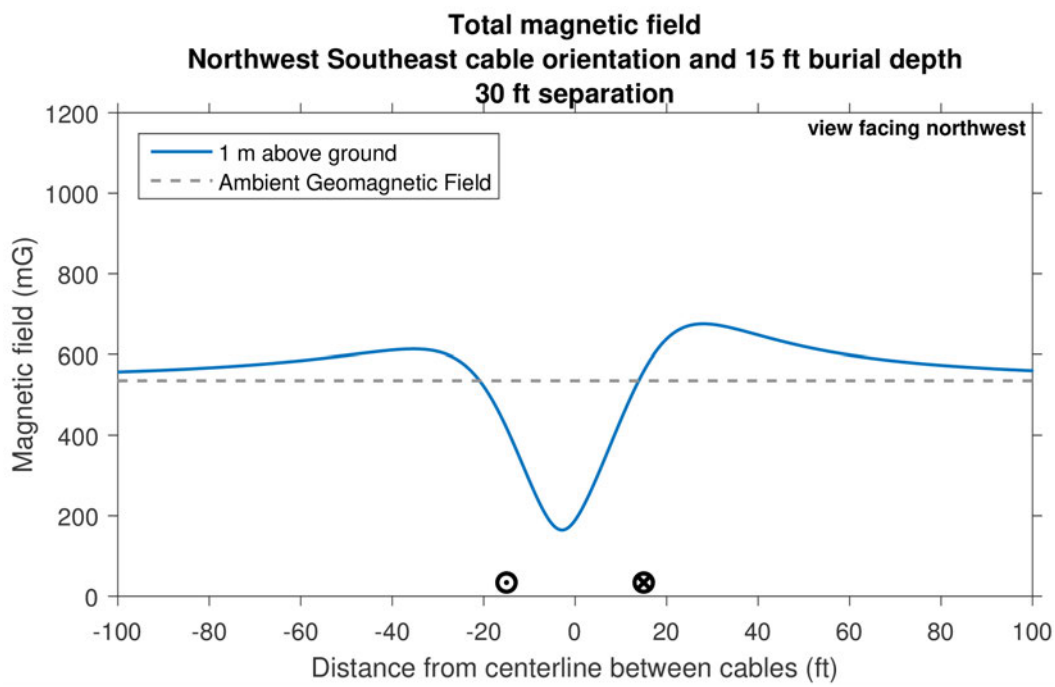

Figure A- 1 Configuration 1. Total magnetic field (cable + ambient geomagnetic) calculated at 1 meter above ground for DC cables oriented northwest-southeast, buried 15 feet underground, separated by 30 feet, with northwestward current in the southwestern conductor.

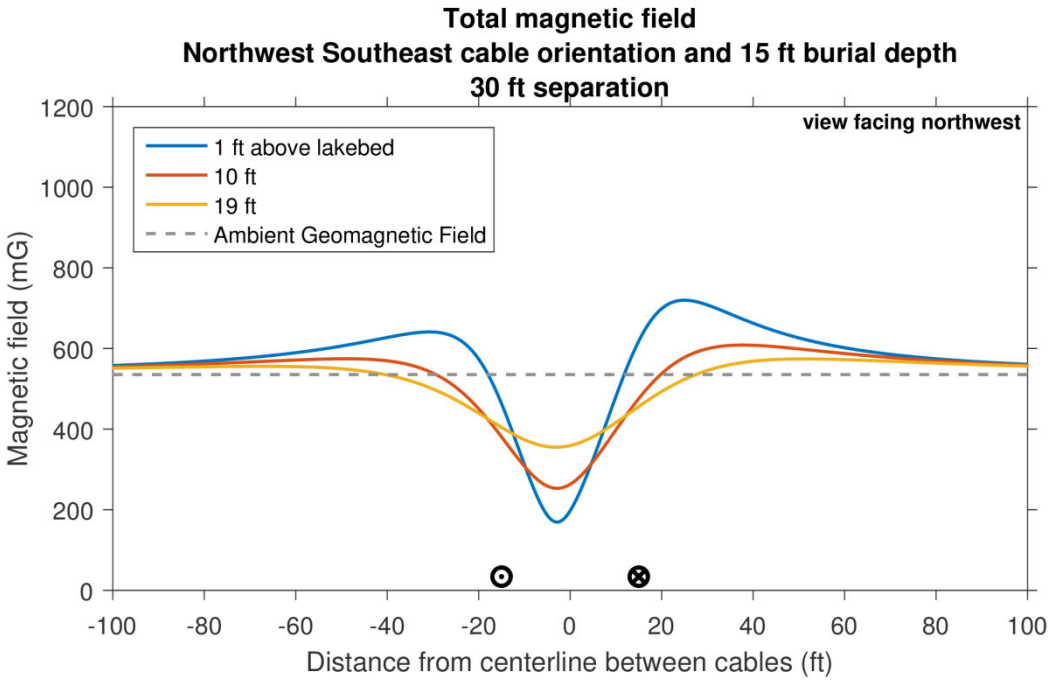

Figure A-2 Configuration 1b. Total magnetic field (cable + ambient geomagnetic) calculated at 1 foot, 10 feet, and 19 feet above lakebed for DC cables oriented northwest-southeast, buried 15 feet underwater, separated by 30 feet, with northwestward current in the southwestern conductor.

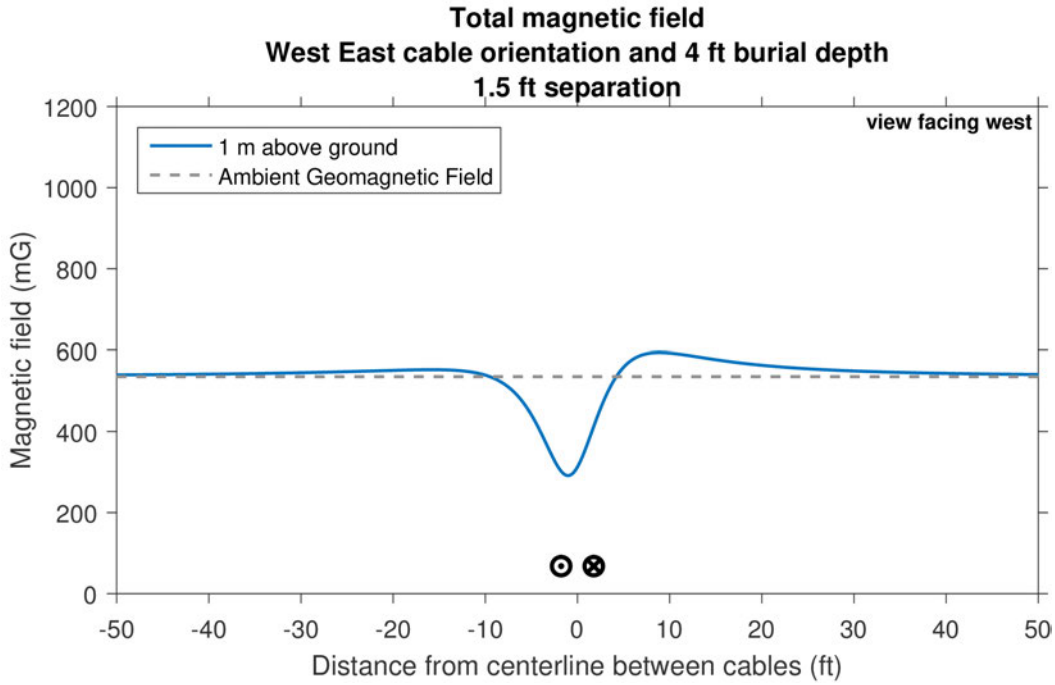

Figure. A-3 Configuration 2. Total magnetic field (cable + ambient geomagnetic) calculated at 1 meter above ground for DC cables oriented west-east, buried 4 feet underground, separated by 1.5 feet, with westward current in the southern conductor.

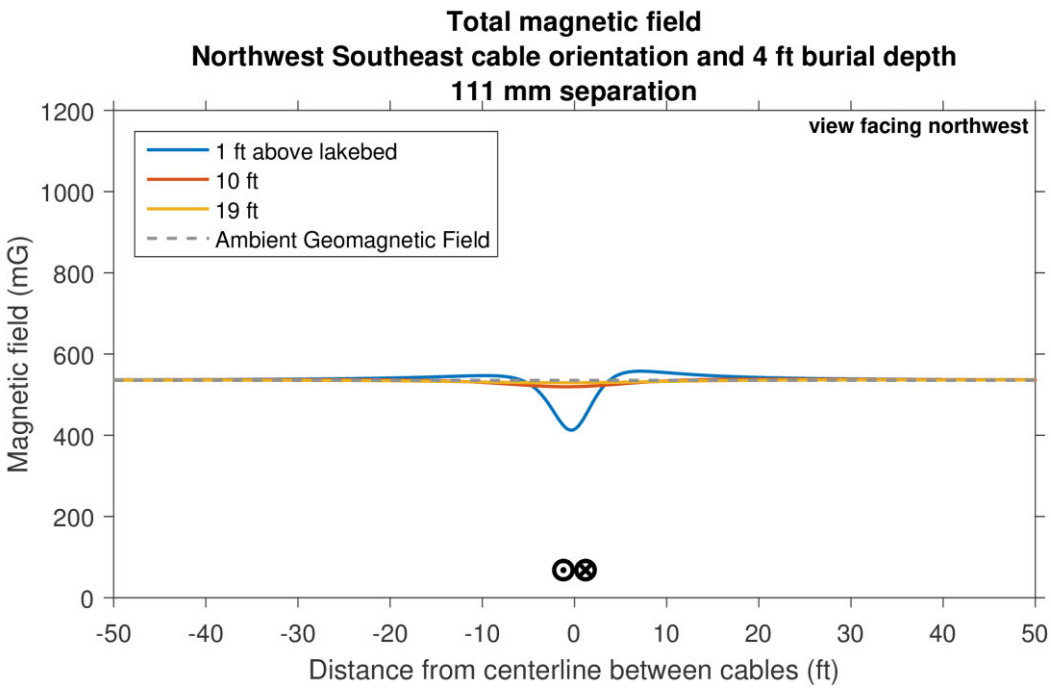

Figure. A-4 Configuration 3. Total magnetic field (cable + ambient geomagnetic) calculated at 1 foot, 10 feet, and 19 feet above lakebed for DC cables oriented northwest-southeast, buried 4 feet underwater, separated by 111 mm, with northwestward current in the southwestern conductor.

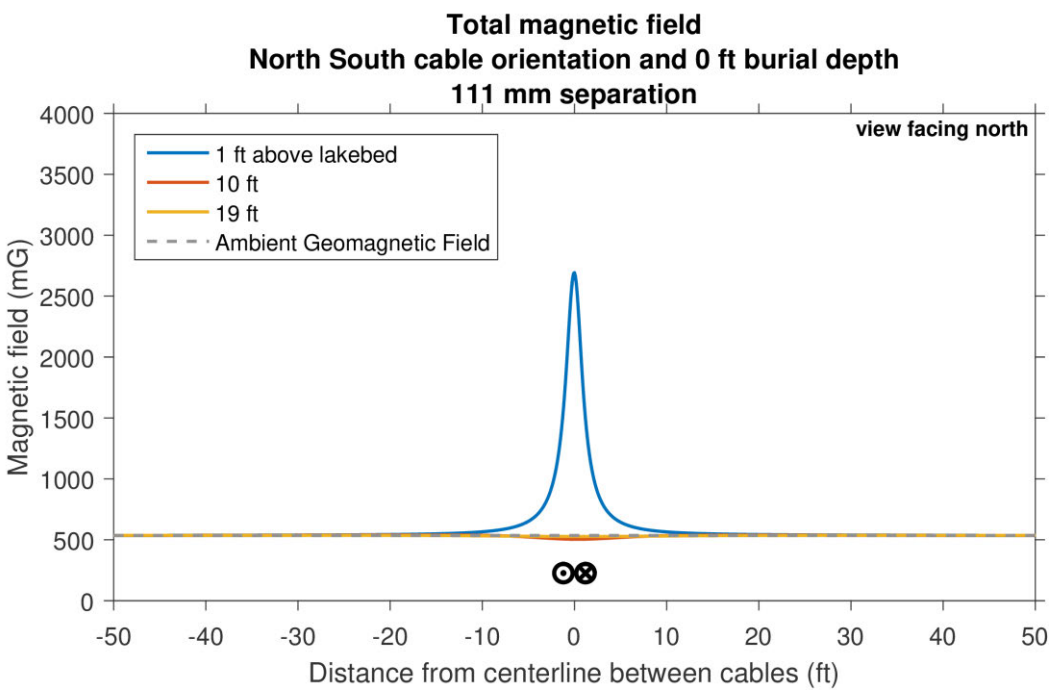

Figure. A- 5 Configuration 4. Total magnetic field (cable + ambient geomagnetic) calculated at 1 foot, 10 feet, and 19 feet above lakebed for DC cables oriented north-south, lying underwater on the surface of the lakebed, separated by 111 mm, with northward current in the western conductor. Note that the y-axis scale is different than that in Figure A-1

Table A-1. Configuration 1a - magnetic-field magnitude deviation (mG) from 535 mG geomagnetic field 1 meter above ground with DC cables in northwest-southeast orientation

Cable burial depth and phasing	Distance from circuit centerline							
	-50 feet	-25 feet	-10 feet	Max + deviation	Max - deviation	+10 feet	+25 feet	+50 feet
15 feet (northwestward current in the southwestern conductor)	61	45	-249	139	-372	-98	135	83

Table A- 2. Configuration 1b - magnetic-field magnitude deviation (mG) from 535 mG geomagnetic field above the lakebed with DC cables in northwest-southeast orientation

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
15 feet (northwestward current in the southwestern conductor)	1	70	91	-224	183	-367	-56	183	90
	10	38	-33	-229	72	-283	-138	42	63
	19	13	-64	-162	38	-181	-120	-13	38

Table A-3. Configuration 2 - magnetic-field magnitude deviation (mG) from 535 mG geomagnetic field 1 meter above ground DC cables in west-east orientation

Cable burial depth and phasing	Distance from circuit centerline							
	-50 feet	-25 feet	-10 feet	Max + deviation	Max - deviation	+10 feet	+25 feet	+50 feet
4 feet (westward current in the northern conductor)	3.2	11	2.7	58	-245	57	18	4.2

Table A-4. Configuration 3 – magnetic field magnitude deviation (mG) from 535 mG geomagnetic field above the lakebed with DC cables in northwest-southeast orientation

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
4 feet (northwestward current in the northeastern conductor)	1	0.1	3.0	11	21	-124	18	3.7	0.2
	10	-0.2	0.3	-6.2	1.7	-17	-2.4	1.5	0.0
	19	-0.5	-1.3	-5.1	0.0	-6.9	-3.7	-0.3	-0.2

Table A-5. Configuration 4 - magnetic-field magnitude deviation (mG) from 535 mG geomagnetic field above the lakebed with DC cables in north-south orientation

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
0 feet (northward current in the eastern conductor)	1	0.2	3.9	30	2157	-1.0	29	3.8	0.2
	10	0.1	2.3	0.6	3.5	-32	-2.2	1.8	0.0
	19	-0.2	0.1	-4.3	0.2	-9.6	-5.3	-0.5	-0.3

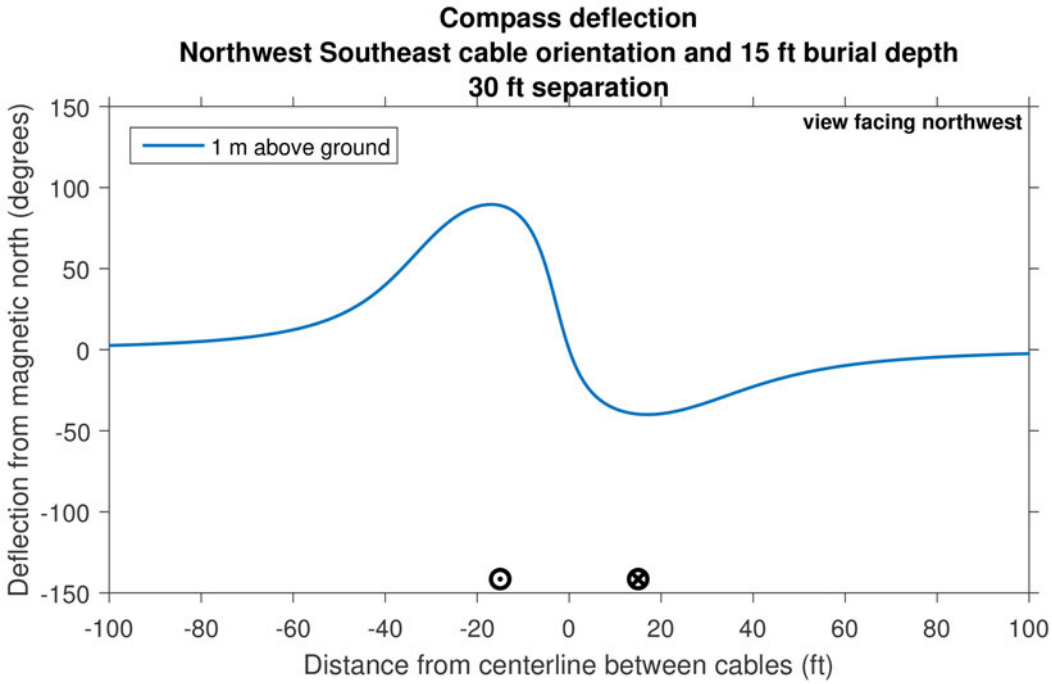

Figure A-6 Configuration 1. Compass deflection (degrees) from magnetic north 1 meter above ground for DC cables oriented northwest-southeast, buried 15 feet underground, separated by 30 feet, with northwestward current in the southwestern conductor.

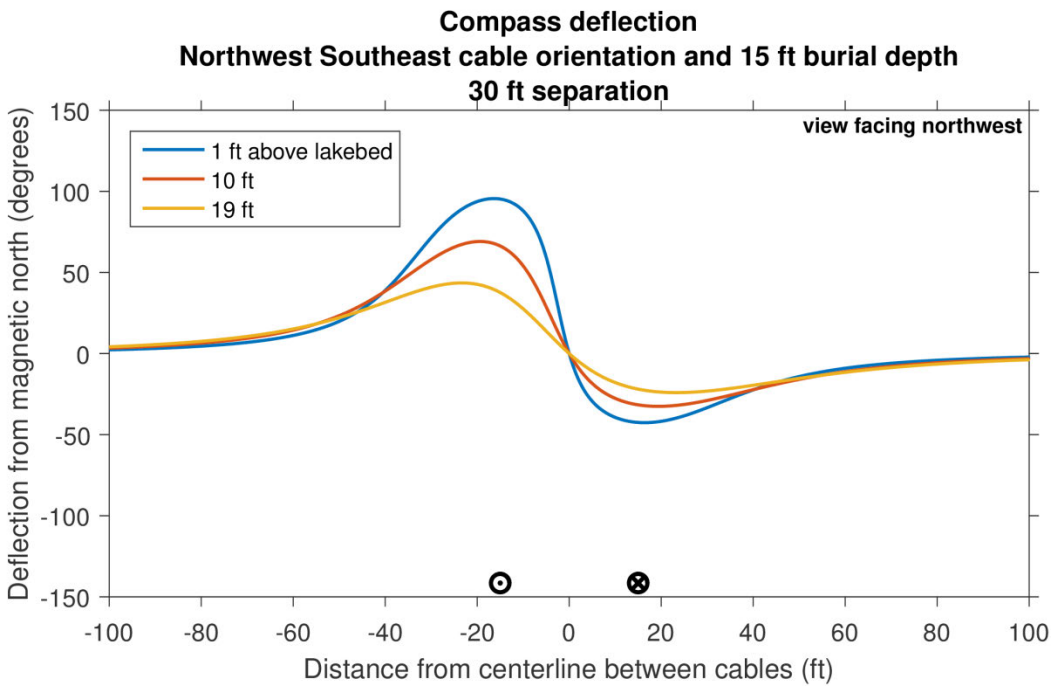

Figure A-7 Configuration 1b. Compass deflection (degrees) from magnetic north 1 foot, 10 feet, and 19 feet above the lakebed for DC cables oriented northwest-southeast, buried 15 feet underwater, separated by 30 feet, with northwestward current in the southwestern conductor.

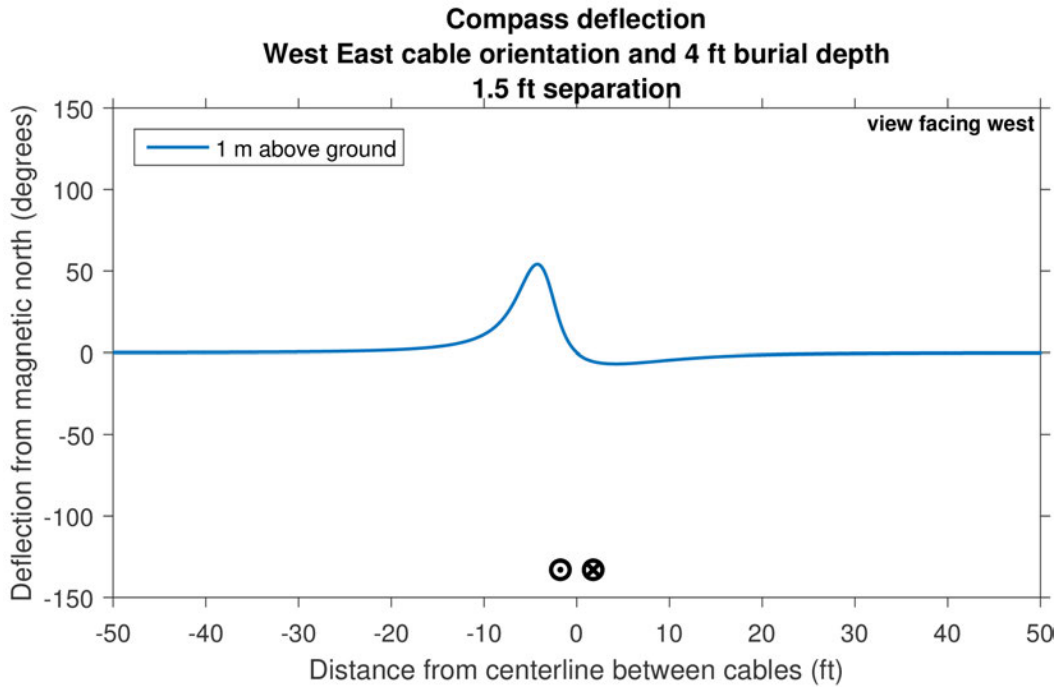

Figure A-8 Configuration 2. Compass deflection (degrees) from magnetic north 1 meter above ground for DC cables oriented west-east, buried 4 feet underground, separated by 1.5 feet, with westward current in the southern conductor.

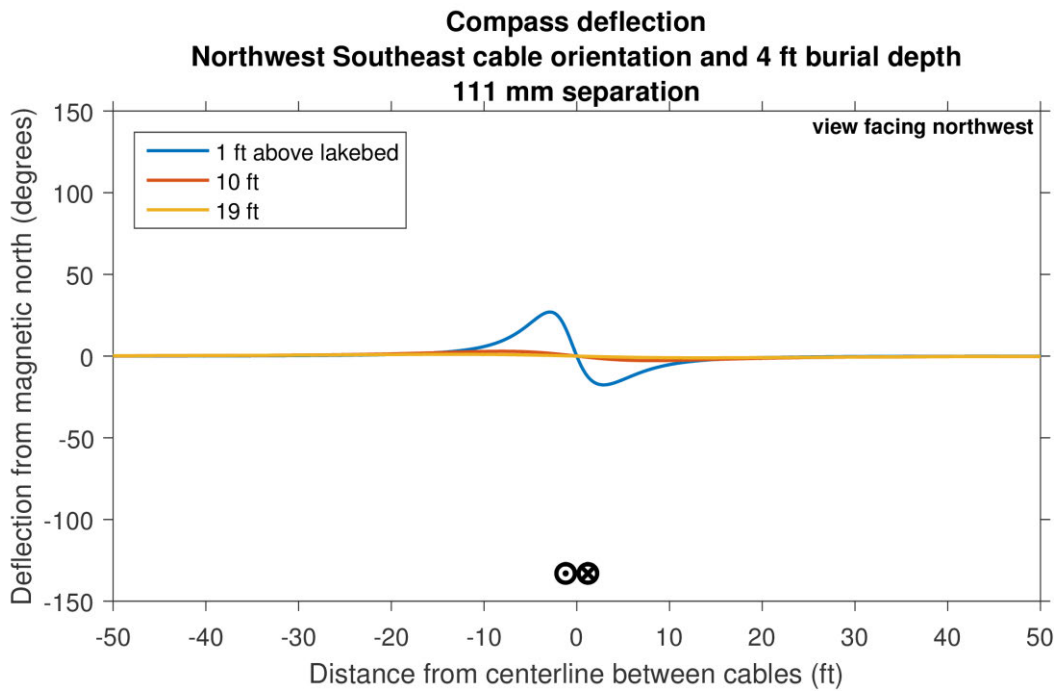

Figure A-9 Configuration 3. Compass deflection (degrees) from magnetic north 1 foot, 10 feet, and 19 feet above the lakebed for DC cables oriented northwest-southeast, buried 4 feet underwater, separated by 111 mm, with northwestward current in the southwestern conductor.

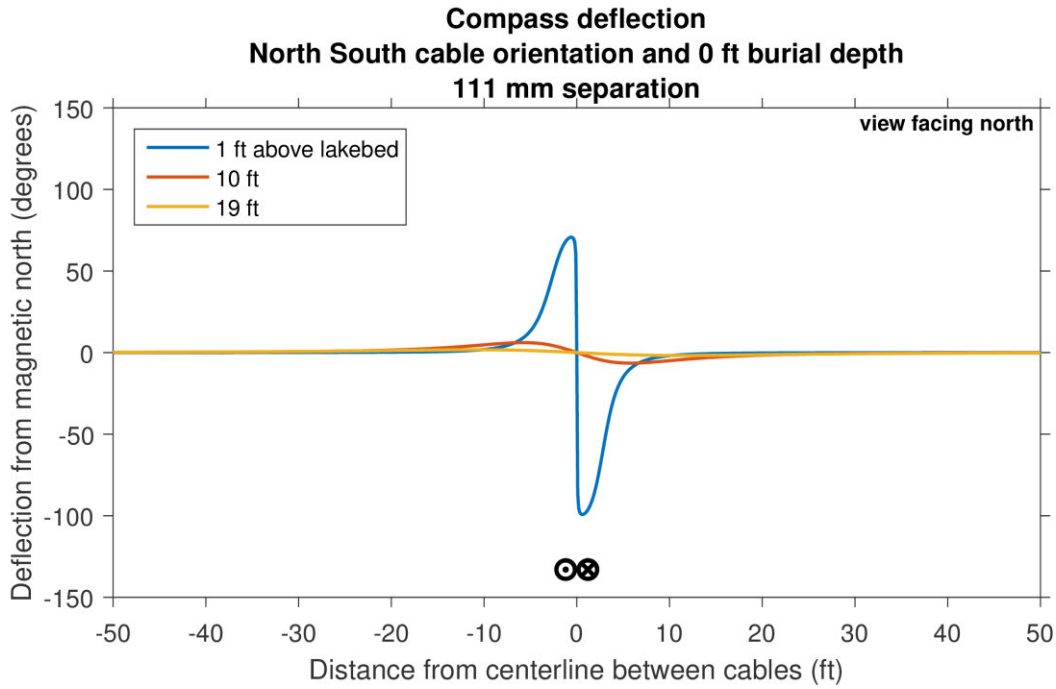

Figure A-10 Configuration 4. Compass deflection (degrees) from magnetic north 1 foot, 10 feet, and 19 feet above the lakebed for DC cables oriented north-south, lying underwater on the surface of the lakebed, separated by 111 mm, with northward current in the western conductor.

Table A-6. Configuration 1a − compass deflection (degrees) from magnetic north 1 meter above ground with DC cables in northwest-southeast orientation.

Cable burial depth and phasing	Distance from circuit centerline							
	-50 feet	-25 feet	-10 feet	Max + deviation	Max - deviation	+10 feet	+25 feet	+50 feet
15 feet (northwestward current in the southwestern conductor)	21	81	80	90	-40	-36	-37	-15

Table A-7. Configuration 1b − compass deflection (degrees) from magnetic north 1 meter above the lakebed DC cables in northwest-southeast orientation

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
15 feet (northwestward current in the southwestern conductor)	1	20	86	88	96	-43	-39	-38	-14
	10	23	66	54	69	-33	-28	-31	-16
	19	22	43	28	44	-24	-18	-24	-15

Table A-8. Configuration 2 − compass deflection (degrees) from magnetic north 1 meter above ground with DC cables in west-east orientation

Cable burial depth and phasing	Distance from circuit centerline							
	-50 feet	-25 feet	-10 feet	Max + deviation	Max - deviation	+10 feet	+25 feet	+50 feet
4 feet (westward current in the northern conductor)	0.1	0.9	11.1	54	-6.7	-4.4	-0.8	-0.1

Table A-9. Configuration 3 − compass deflection (degrees) from magnetic north, above the lakebed with DC cables in northwest-southeast orientation

Cable burial depth and phasing	Height above lakebed (feet)	Distance from circuit centerline							
		-50 feet	-25 ft	-10 ft	Max + deviation	Max - deviation	+10 ft	+25 ft	+50 ft
4 feet (northwestward current in the northeastern conductor)	1	0.1	0.5	5.8	27	-18	-5.2	-0.5	-0.1
	10	0.2	0.9	2.8	2.9	-2.8	-2.7	-0.9	-0.2
	19	0.2	0.8	1.0	1.1	-1.0	-1.0	-0.7	-0.2

Table A-10. Configuration 4 − compass deflection (degrees) from magnetic north, above the lakebed with DC cables in north-south orientation

Cable burial depth and phasing	Height above lakebed (feet)	Distance from circuit centerline							
		-50 ft	-25 ft	-10 ft	Max + deviation	Max - deviation	+10 ft	+25 ft	+50 ft
0 feet (northward current in the eastern conductor)	1	0.0	0.1	1.9	71	-99	-1.9	-0.1	0.0
	10	0.1	0.9	4.7	6.1	-6.5	-5.0	-0.9	-0.1
	19	0.2	0.9	1.7	1.7	-1.8	-1.8	-1.0	-0.2

Appendix B

Modeling of AC Magnetic Fields

Assessment Criteria

Electric currents flowing in AC transmission lines generate AC magnetic fields, and this section describes and evaluates the potential for effects of those magnetic fields. While neither the federal government nor the state of Vermont has regulations for power frequency magnetic fields, guidelines developed by the International Commission on Non-ionizing Radiation Protection (ICNIRP) and the International Committee on Electromagnetic Safety (ICES) protect public health and safety by limiting exposure to power frequency magnetic fields. These international organizations base their exposure limits on extensive reviews and evaluations of relevant health research. These magnetic-field exposure limits are summarized in Table B-1 and are used as criteria to evaluate the proposed AC transmission lines and their potential effects on the electrical environment.

Table B-1. Exposure limits for AC magnetic fields

Agency	Magnetic Fields (mG)	Comment
ICNIRP	2,000	General public exposure limit
ICES	9,040	General public exposure limit

Methodology

AC magnetic-field levels were calculated at 1 m above ground as the root mean square (RMS) value of the field in accordance with IEEE Std. C95.3.1-2010 and IEEE Std. 644-1994 (Rev. 2008), and were calculated as the resultant of the x, y, and z field vectors. Calculations used computer algorithms developed by the Bonneville Power Administration, an agency of the U.S. Department of Energy (BPA, 1991). Each conductor was modeled as infinite in length at a fixed burial depth relative to a flat, infinite earth, and each conductor was assumed to be parallel to all other conductors.

The inputs to the algorithm include current, phasing, and conductor configurations for each transmission line on the ROW. The proposed AC line is to be installed at the center of a 30 ft ROW with the phase conductors in a trefoil configuration (each phase separated by a center-center distance of 25 inches) at 15 ft burial depth. Magnetic-field levels will be analyzed at ROW edge and as a function of horizontal distance from the centerline of the AC line. Specifications of data input to our magnetic-field calculations are detailed in Table B-2.[1]

Table B-2. Input data for magnetic field calculations

Bundle	x (feet)	y (feet)	Current (A)	Phase (degrees)
1	0.0	-15.2	700	0
2	-1.0	-17.6	700	120
3	1.0	-17.6	700	240

[1] Additional information needed for calculating electric fields are not included in this table because electric fields from the underground lines are not calculated.

Results & Analysis

The magnetic-field levels along a transect perpendicular to the proposed AC line are plotted in Figure B-1. Dashed grey lines mark the proposed ROW edge locations at ±15 ft from the circuit centerline. Tabulated magnetic-field levels at distances of ±15 ft, ±25 ft, and ±50 ft from the circuit centerline are presented in Table B-3

The calculated magnetic-field level achieves its maximum near the circuit centerline and decreases rapidly with distance. At the edges of the ROW, ±15 ft from the circuit centerline, all calculated magnetic-field levels are below 20 mG, and at ±50 ft from each circuit centerline, all calculated magnetic-field levels are below 5 mG. Such values are similar to those under lower-voltage distribution lines (Savitz et al., 1989). Magnetic-field levels below 20 mG are less than 1% of either the ICES or ICNIRP guidelines for general public exposure to power frequency magnetic fields.

Table B-3. Magnetic-field levels (mG) for distances from AC circuit centerline

	Distance from circuit centerline						
Circuit Loading	**−50 ft**	**−25 ft**	**−15 ft**	**Max**	**+15 ft**	**+25 ft**	**+50 ft**
700 A	4.1	12	19	30	19	12	4.1

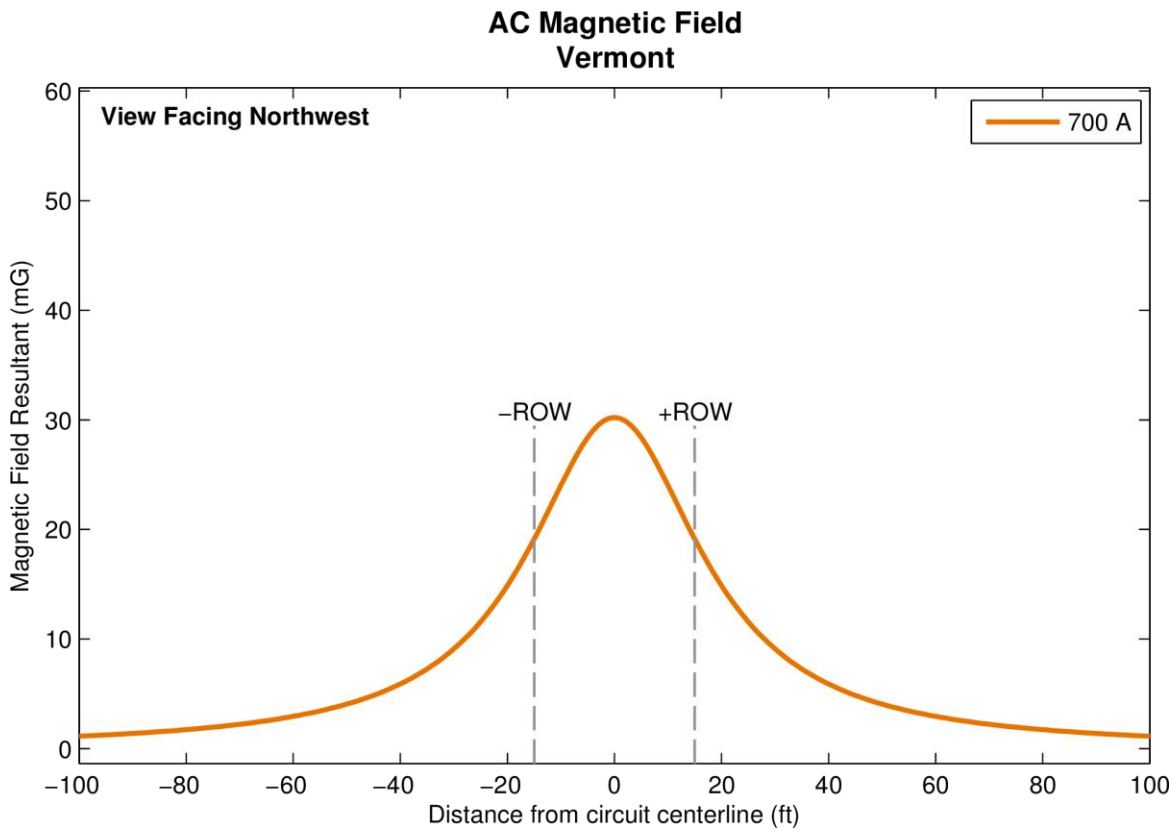

Figure B-1. Magnetic-field levels along a transect perpendicular to the proposed 345-kV AC line. Results are shown for expected loading (700 A).