Bipole III Transmission Project

Electromagnetic Fields (EMF) Technical Report

Exponent Inc.
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Manitoba Hydro

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Health Sciences Practice

Manitoba Hydro Bipole III

Environmental and Health Assessment of the Electrical Environment

Direct Current Electric and Magnetic Fields and Corona Phenomena

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Prepared for

Manitoba Hydro

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Acronyms and Abbreviations

μA	Microampere
μm	Micrometre
μT	Microtesla
A	Ampere
AC	Alternating current
ACGIH	American Conference of Governmental Industrial Hygienists
AGNIR	Advisory Group on Non-Ionising Radiation
AM	Amplitude modulated
AN	Audible noise
cm	Centimetre
dB	Decibels
dB-A	Decibels on the A-weighted scale
DC	Direct current
DGPS	Differential global positioning system
ESD	Electrostatic discharge
FDA	US Food and Drug Administration
Fe_3O_4	Magnetite
FM	Frequency modulated
G	Gauss
GHz	Gigahertz
GΩ	Giga-ohm
GNSS	Global navigation satellite system
GPS	Global positioning system
HEM	Helicopter electromagnetic
Hz	Hertz
IARC	International Agency for Research on Cancer
ICES	International Committee on Electromagnetic Safety
ICNIRP	International Commission for Non-Ionizing Radiation Protection
IEC	International Electrotechnical Commission
Ions/cm^3	Ions per square centimetre
kHz	Kilohertz
km	Kilometre
kV	Kilovolt
kV/cm	Kilovolt per centimetre
kV/m	Kilovolt per metre

m	Metre
MEQB	Minnesota Environmental Quality Board
mG	Milligauss
MHz	Megahertz
MHRF	Ministry of Health of the Russian Federation
mm	Millimetre
mT	Millitesla
MRI	Magnetic resonance imaging
MSAT	Mobile satellite
MW	Megawatt
mV	Millivolt
nA/m^2	Nanoamperes per square metre
NDGPS	Nationwide differential global positioning system
nm	Nanometre
NRPB	National Radiation Protection Board of Great Britain
nT	Nanotesla
O_3	Ozone
ppb	Parts per billion
Rad/s	Radians per second
RF	Radiofrequency
RMS	Root mean square
RN	Radio noise
ROW	Right-of-way
RTK	Real-time kinetic
T	Tesla
SCENIHR	Scientific Committee for Emerging and Newly Identified Health Risks
SPL	Sound pressure level
UHF	Ultra high frequency
VDU	Video display units
VHF	Very high frequency
V/m	Volts per metre
WHO	World Health Organization

Unit Definitions and Conversions

Multiple units are often used to quantify levels of the same electrical phenomenon. The following tables are provided to assist the reader in understanding the relationship of different units for common electrical phenomenon (current, voltage, electric fields, and magnetic fields). The relationship between magnetic flux density (B), expressed in Tesla (T) and magnetic field (H), expressed in Amperes/metre (A/m), , is given by B = μH where μ is the magnetic permeability of the medium. The permeability of biological materials and water is similar to that of air μ_0 (1.257×10^{-6} Henries/metre) so that 1 T = 7.96×10^{5} A/m.

Current

Unit	Abbreviation	Conversion to A
Ampere	A	
Milliampere	mA	0.001 A
Microampere	μA	0.000001 A
Nanoampere	nA	0.000000001 A

Voltage

Unit	Abbreviation	Conversion to V
Volt	V	
Kilovolt	kV	1,000 V
Millivolt	mV	0.001 V
Microvolt	μV	0.000001 V

Electric Field

Unit	Abbreviation	Conversion to V/m
Volt/metre	V/m	
Kilovolt/metre	kV/m	1,000 V/m

Magnetic Flux Density (i.e., Magnetic Field)

Unit	Abbreviation	Conversion
Gauss	G	
Milligauss	mG	0.001 G = 0.1 μT
Tesla	T	1 Weber/m^2
Millitesla	mT	0.001 T = 10 G
Microtesla	μT	0.000001T = 10 mG
Nanotesla	nT	0.000000001 T = 0.01 mG

Notice

At the request of Manitoba Hydro, Exponent conducted specific modeling and evaluations of components of the electrical environment of the Bipole III project. This report summarizes work performed to date and presents the findings resulting from that work. In the analysis, we have relied on geometry, material data, usage conditions, specifications, regulatory status, and various other types of information provided by the client. We cannot verify the correctness of this input data, and rely on the client for their accuracy. Although Exponent has exercised usual and customary care in the conduct of this analysis, the responsibility for the design and operation of the project remains fully with the client.

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 investigation 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 herein 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.

Executive Summary

The components of the Bipole III project—transmission lines, converter stations, and ground electrodes—are all sources of direct current (DC) electric and magnetic fields and related corona phenomena, including space charge (air ions and charged aerosols), audible noise (AN), and radio noise (RN).

The purpose of this assessment is to describe the exposures associated with these components of the Bipole III electrical environment and to determine if and how exposure may affect humans, domestic animals, wildlife, and plants in the project area.

DC electric and magnetic fields (also called static fields because of their unvarying nature in time) **and space charge** are everywhere in the natural environment. The most prevalent static magnetic field is produced by the Earth as a result of constant flow of current deep within the Earth's core. This is called the Earth's geomagnetic field and it is this field that is used for compass navigation. Static electric fields are produced by many natural phenomena including that produced by charges accumulated on clothing after walking across a carpet. Other common natural sources of DC electric fields include weather phenomena such as storm clouds, blowing snow, and swirling dust clouds.

Electrical charges in the air, referred to as **space charge,** are formed by many common natural sources: by the Earth and its atmosphere, energy released by evaporation (i.e., the break-up of water droplets), friction from blowing snow and swirling dust, open flames and other combustion processes, and various meteorological events. These charges may provide the basis for a clustering of gas molecules (air ions) or may become attached to passing solid or liquid particles (charged aerosols). Collectively, air ions charged aerosols are referred to as space charge.

The changes to the background electrical environment expected from the operation of Bipole III were modeled and the resulting levels compared to relevant standards and guidelines. In addition, numerous reviews of the scientific literature by scientific and regulatory agencies on static electric and magnetic fields and related phenomena were consulted including those by the

American Conference of Governmental Industrial Hygienists (ACGIH), Health Canada, the International Agency for Research on Cancer (IARC), the International Commission on Non-ionizing Radiation Protection (ICNIRP), the International Committee on Electromagnetic Safety (ICES), the Minnesota Environmental Quality Board (MEQB), the National Radiological Protection Board (NRPB), the U.S. Food and Drug Administration (FDA), and the World Health Organization (WHO).

DC electric fields from the Bipole III line are not capable of coupling effectively to conductive objects and so the currents intercepted by a person under a DC transmission line are on the order of a few microamperes (μA), which is below the threshold for detection of DC currents. Even for large vehicles parked underneath a DC transmission line or long parallel fences, the charge collected is limited by leakage current to the ground so the possibility of perception is limited; under experimental 'worst case' conditions, the only noticeable effect of touching a large, well grounded vehicle would be a microshock, weaker than what a person might experience after crossing a carpet.

The static magnetic field will be increased above background levels on portions of the right-of-way (ROW) and decreased below background levels on other portions of the ROW. Outside the ROW, there will be an insignificant change in the background geomagnetic field.

When the strength of the electric field at points on the conductor surface exceeds a threshold or onset level, a small amount of energy is released by a partial electrical discharge (called corona) that can lead to air ions, charged aerosols, audible noise (AN), and radio noise (RN). There are no guidelines for exposures to air ions and charged aerosols, but the modeled levels outside the ROW are expected to be similar to those of other DC transmission lines in North America and within the range of levels produced by other ambient sources. The levels of AN will be well below provincial standards and RN will be well below the national Canadian standard.

The proliferation of electronic devices for personal, recreational, commercial, and medical uses had prompted questions as to whether the Bipole III transmission line will affect their performance. The Global Positioning System (GPS) is a space-based navigation system that relies on 24 orbiting satellites circling Earth to establish the position of a GPS receiver on the Earth. The receiver uses the radiofrequency (RF) signals sent from three or more of these satellites to determine its exact location. Naturally-occurring sources of RF (e.g., geomagnetic storms) and man-made sources of RF (e.g., TV station transmitters) are sometimes reported to interfere with GPS signals because these sources produce RF in the same frequency range as the GPS. Since GPS signals are of far higher frequency than the RN produced by a DC transmission line, however, it is very unlikely that a DC transmission line will interfere with GPS functioning. In addition, tests of a variety of GPS receivers performed for Manitoba Hydro under the existing Bipole I and II transmission lines were unable to detect any impairment in GPS performance due to RN.

The northern portion of the project study area includes mining leases within the Thompson Nickel Belt and sensitive electronic methods are used in surveys to detect conductive ore deposits. Whether the fields from the proposed Bipole III transmission line will interfere with mining exploration survey methods depends on the distance to the line, the type of measurement equipment used for the explorations, and post-processing corrections of the acquired data. Mitigation methods include avoiding or minimizing potential interference with mining exploration by encouraging mining companies to conduct surveys before the construction of Bipole III in 2017, applying filters during post-survey processing to remove extraneous magnetic 'noise,' using survey methods less susceptible to interference, and shifting the route of the line further from mining claims.

The magnetic field from a DC line is too weak to affect cardiac pacemakers. Since the background level of the static magnetic field in Manitoba is approximately 580 milligauss (mG) (58 microtesla [µT]) and the maximum increase from Bipole III is estimated to be less than twice this background level, the exposures to a person with an implanted pacemaker even under the transmission line will be far below the recommended exposure limit of 0.5 millitesla (mT) (5,000 mG) (ACGIH, 2009). Similarly, the static electric field from a DC line would not be expected to be a source of interference to a pacemaker or cause human-body potentials to exceed the International Electrotechnical Commission's (IEC) immunity-test levels for a cochlear implant.

Converter stations (where alternating current [AC] power is converted to DC power and vice versa) and the ground electrodes at each end of the line are necessary for operation of the Bipole

III line. The levels of DC electric fields and magnetic fields from these sources are low outside the facility property. During some modes of monopolar operation prompted by maintenance or equipment breakdown, the full load current may be carried on a feeder line to the ground electrode to complete the circuit via a conductive path deep in the Earth. The magnetic field at points under the electrode line and at line termination would be higher than on the Bipole III ROW but still very low and well below international standards. Based on evaluations performed by Teshmont of step potentials and other considerations, temporary monopolar operation would not pose risks to the safety of persons and animals. Confirmation of these results under a wider range of assumptions and the calculation of touch potential is recommended. While incomplete filtering of harmonic currents at the converter station in monopolar operation might cause interference to nearby susceptible telephone communications, this possibility can be reduced in the design stage, or mitigated if further reductions are required later.

In summary, the electrical environment is expected to conform to exposure limits recommended by provincial, national, and international agencies. A comparison between Bipole III and six other DC transmission lines in North America shows that the median peak levels of DC electric fields and small air ions of Bipole III are lower than the levels of five other DC transmission lines. The field levels of the proposed line were not found to pose any likely effect on electronic devices nor were adverse effects of the ground electrode/feeder line identified that could not be mitigated.

It is noted that this Executive Summary cannot summarize all of Exponent's technical evaluation, analysis, conclusions, and recommendations. Hence, the main part of this report and its Appendices are at all times the controlling document.

Introduction

Manitoba Hydro has proposed to construct a new ±500-kilovolt (kV) direct current (DC) transmission line (Bipole III). Bipole III will link the existing northern power generating facilities on the Nelson River with the existing alternating current (AC) system that delivers electricity to homes, offices, factories, and other facilities in southern Manitoba. Manitoba currently has two DC transmission lines, Bipole I and Bipole II on the same corridor, which carry power generated on the Nelson River to the greater Winnipeg area. The addition of Bipole III to a different corridor will improve the reliability of the province's electricity supply.

DC transmission was selected for this particular project because it is more effective in transmitting electricity over long distances than AC transmission. Foremost, DC transmission has less power loss because of the direct nature of current flow; AC electricity flows more at the surface of the conductors, which results in higher resistance and more line losses. DC transmission also requires less extensive facilities—smaller towers and fewer insulators and conductors—than AC transmission. The major issue that can offset these advantages is the cost and complexity of converting between AC and DC power. For this reason, DC transmission lines are most practical in the circumstance where a large amount of power is being transmitted over a long distance, without the need to tap power off along the way (e.g., only two converter stations needed).

The preferred route is approximately 1,384 kilometres (km) (Figure 1). The route will originate near Gillam (Keewatinoow); it will continue west and south towards The Pas; it will proceed south to the west of Lake Winnipegosis and Lake Manitoba; and it will pass south of Portage la Prairie and Winnipeg. Finally, the route will terminate at the Riel Converter Station in the rural municipality of Springfield.

Converter stations are also required to convert the AC power from the generators to DC power and then back to AC power for distribution. The project consists of building two, new converter stations—one northeast of Gillam (Keewatinoow) in northern Manitoba and the other east of Winnipeg at the Riel Station site. In addition, Manitoba Hydro plans to install two ground electrodes, one connected to each converter station. Finally, 230-kV AC transmission line interconnections will tie the new Keewatinoow converter station into the existing AC transmission system and generating stations in North Manitoba. The electrical environment and assessment of these 230-kV AC lines are the subject of another Exponent report "Environmental and Health Assessment of the Electrical Environment—Alternating Current Electric and Magnetic Fields and Corona Phenomena."

The conductors of the proposed DC transmission line will be strung on steel tower structures on a 66 metre (m) wide right-of-way (ROW). The towers will be spaced approximately 480 m apart, resulting in two to three towers per km (i.e., three to four towers per mile). Two types of towers will be used, depending on the area's terrain: self-supporting lattice towers will be used in agricultural areas to minimize the impact on agricultural operations and guyed towers will be used in forested areas and other suitable areas.

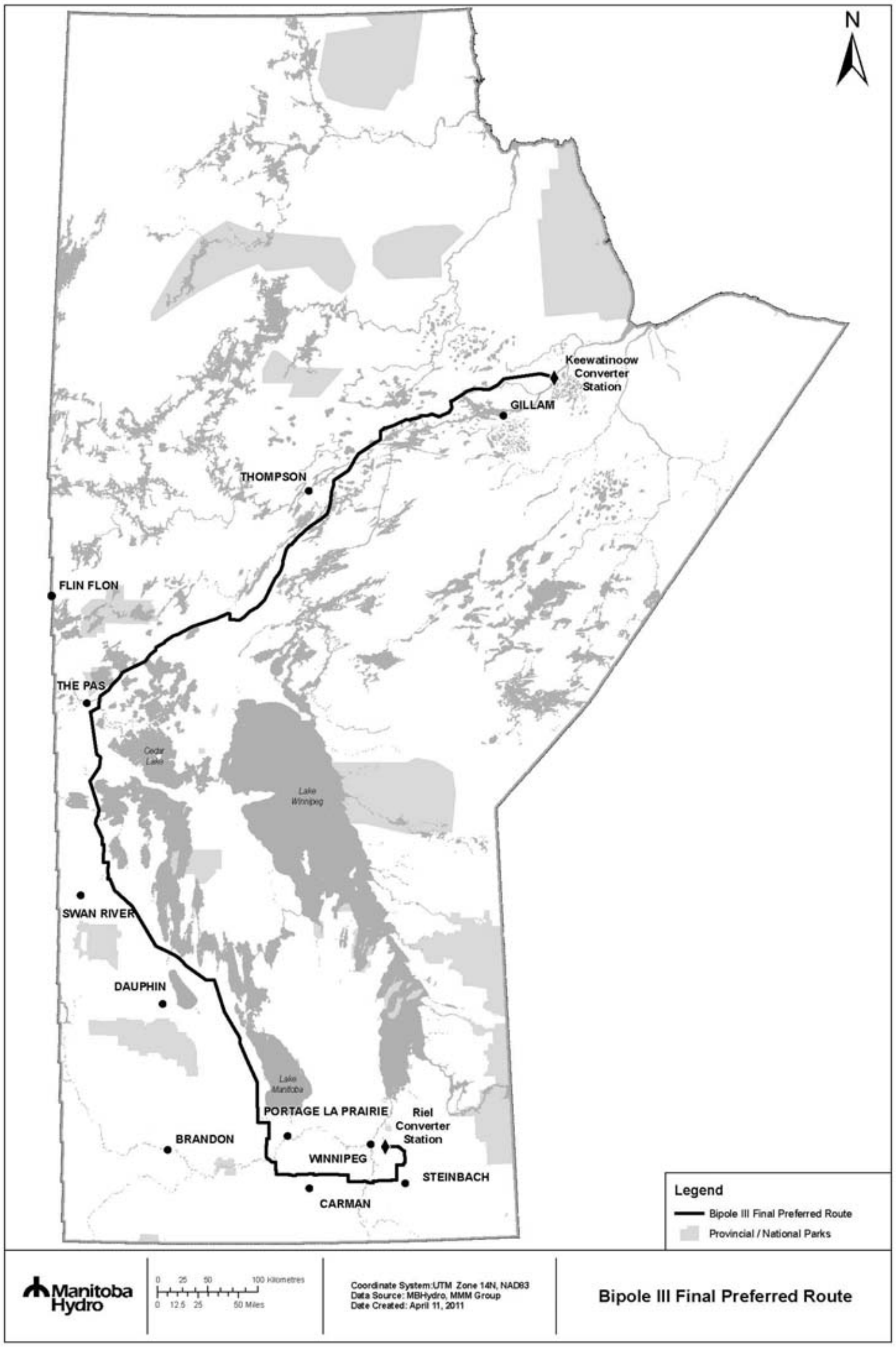

Figure 1. Bipole III preferred route

The components of the Bipole III project—transmission lines, converter stations, and substations—are all sources of electric and magnetic fields and related corona phenomena including space charge (small air ions and charged aerosols), audible noise (AN), and radio noise (RN).

During the consultation process comments from the public raised questions about electric and magnetic fields in relation to general health, animals, research, electronics and machinery, and medical devices, which resulted in electric fields, magnetic fields, and related phenomena being the fourth most common topic.[1] The purpose of this assessment is to determine if and how the operation of these project components may affect humans, domestic animals, wildlife, and plants in the project area, and in so doing address the issues raised by these comments. Specific criteria are used to evaluate the possible impact of the electrical environment, as described in the Methodology section below. Other sections of this report include the following:

- **The Nature of the Electrical Environment** summarizes the basic properties of the study areas for this report (i.e., DC electric and magnetic fields and corona phenomena), including sources and typical exposure levels.

- **Scientific Reviews and Guidelines for Direct Current Electric and Magnetic Fields** summarizes the conclusions of reviews published by scientific agencies related to DC fields and corona ion phenomena. These reviews address the health and safety of humans (a key identified issue for this project) and provide recommended standards and guidelines for levels of DC electric and magnetic fields, AN, and RN. These guidelines provide the criteria used for assessing the impact of the Bipole III project.

- **Electrical Environment of Bipole III – Static Fields** summarizes the calculated levels of static electric and magnetic fields from the proposed Bipole III line, compares them to relevant guidelines, and provides an assessment of the likelihood and nature of any expected impacts.

- **Electrical Environment of Bipole III – Space Charge** summarizes the calculated levels of air ions from the proposed Bipole III line, compares them to other DC lines in North America, and assesses the likelihood and nature of expected impacts based on a review of health-related research and measurements of charged aerosols around the existing Bipole I and II lines in Manitoba.

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[1] Bipole III Newsletter Round Four – Preliminary Preferred Route
http://www.hydro.mb.ca/projects/bipoleIII/bipoleIII_newsletter4.pdf

- **Electrical Environment of Bipole III – Audible Noise and Radio Noise** summarizes the calculated levels of AN and RN from the proposed Bipole III line, compares these levels to relevant guidelines, and provides an assessment of the likelihood and nature of any expected impacts. This section also summarizes the potential for interference to mining surveys, Global Positioning System (GPS) equipment, and electronic medical devices, issues that were raised during stakeholder consultations on this project.

- **Research on Dairy Cattle, Wild Animals, and Plants** reviews the cumulative research related to DC electric and magnetic fields and dairy cattle, wild animals, crops, and natural flora, topics also raised during stakeholder consultations on this project.

Methodology

The procedure for conducting this assessment involves the delineation of study areas, the identification of important issues, and the determination of valid assessment evaluation criteria.

Study areas

While the Bipole III transmission line project encompasses a large geographic area, the potential for interactions of electrical components with the surrounding environment is much more limited. This report describes the nature of these electrical components to provide the reader with an understanding of their basic characteristics and mechanisms of interaction. These phenomena include the following features of the electrical environment surrounding a DC transmission line: (1) the DC electric field, (2) the DC magnetic field, and (3) various corona phenomena, including AN, RN, and space charge.

These study areas are described in detail in the section **The Nature of the Electrical Environment** below.

Issue identification

Technical issues were identified using knowledge of issues addressed during the previous siting process of existing DC transmission lines and from stakeholder input for this specific project. Major issues that were judged to warrant investigation pertaining to the study areas include the effect of these phenomena on the health and safety of humans, animals, and plants. Aspects of the electrical environment that were addressed by measurements around the Bipole I and Bipole II DC transmission lines in Manitoba (Maruvada et al., 1982) continued to warrant discussion in this assessment. Other technical issues for further study and assessment were identified by Exponent scientists and engineers and from stakeholder input at public open house meetings and submissions to Manitoba Hydro. These include an assessment of charged aerosols, the effects of DC electric and magnetic fields on wildlife, and potential interference to electronic devices such as GPS receivers used in agriculture, devices used for mining surveys, and electronic medical devices.

Exposure assessment

To characterize how the Bipole III project might affect the background electrical environment, the DC transmission lines and other DC components (including the converter stations and ground electrodes) were modeled to describe the spatial distribution of fields and currents and site-specific land uses (Appendix 1). The basis for modeling the charging of aerosols by DC lines is not well developed so a field study was also undertaken to measure the levels of charged aerosols upwind and downwind of the existing Bipole I/II transmission lines in the province.

Criteria for impact assessment

Criteria by which to distinguish potentially significant effects of the Bipole III project on health and the environment were identified by reference to published scientific reviews by national and international agencies, specifically the guidelines and standards established by these agencies. These guidelines and standards serve as criteria for the assessment of DC electric fields, DC magnetic fields, AN, and RN.

No such established criterion for the assessment of air ions was identified. Therefore, to provide a solid basis for conclusions on this topic a weight-of-evidence review of individual research studies was performed using the standard scientific methods recommended and followed by health and scientific agencies. The review of this research, including supplemental tables summarizing each study, is included as Appendix 2.

The Nature of the Electrical Environment

A DC transmission line has two conductors or conductor bundles, called “poles.” The voltages on the poles are usually of opposite polarity—one positive (+) and one negative (-). The operating voltage of a DC transmission line is usually expressed in terms of the voltage on both poles, i.e., Bipole III is described as a ±500-kV transmission line.

The electrical environment surrounding a DC transmission line is primarily influenced by three primary electrical phenomena (a DC electric field, a DC magnetic field, and corona). Other phenomena including AN, RN, ion current density and ozone are secondary to corona discharge.

- The magnetic fields from a DC transmission line arise from the current flowing on the conductors and are commonly expressed as magnetic flux density in units of gauss (G) or milligauss (mG).[2]
- The electric fields from a DC transmission line arise from the voltage on the lines and are measured in units of kilovolts per metre (kV/m). Both DC magnetic and electric fields are identified as “direct” because they do not oscillate over time, or change very slowly (i.e., 0 Hertz [Hz]); for this reason, they also are most often referred to as static fields.[3]
- Corona discharge refers to the partial electric discharge (energy loss) that occurs when the electric field at a point on the conductor is strong enough to remove electrons from air molecules (ionize the air molecules). Corona results in electrical charges being transferred on air molecules referred to as small air ions. These air ions exist only for a matter of seconds before they are neutralized. A fraction of the charge from these air ions is transferred to ambient aerosols, which are then described as charged aerosols.

The general aspects of these electrical factors are fully discussed in this section.

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[2] The magnetic flux density (B) vector is most often used to express the intensity of a magnetic field. In Europe and in technical publications, magnetic flux density is presented in units of tesla (T), the expression used by the International System of Units (Le Système International d'Unités), where 1 T =10,000 G and 1 mG = 0.1 µT. In North America, magnetic flux density is more often expressed in G or mG. See the Unit Definitions and Conversion Charts on page iv.

[3] In comparison, AC electric and magnetic fields from electricity transmitted in North America vary at a frequency of 60 times per second (60 Hz); electricity in other areas of the world may be transmitted at 50 Hz.

Static electric and magnetic fields

Electric and magnetic fields exert forces on electric charges and so are associated with anything that generates, transmits, or uses electricity, both in the AC and DC form. While both AC and DC electricity are sources of electric and magnetic fields, there are substantial differences in the characteristics of these phenomena and, as a result, their potential interactions with people and the environment. These differences stem from the basic fact that current does not alternate when transmitted as DC, while it alternates with a regular frequency when transmitted as AC. As a result of the static nature of DC, there is no significant induction of voltage or current in conductive materials (such as people) with DC fields. Currents are only induced when there is motion by an object or subject in a very high intensity static magnetic field.

Another major difference between AC and DC fields is that DC fields are commonly encountered from many natural sources, as described below. DC fields have been present throughout the evolution of life on Earth and, while this does not preclude any adverse effects, it indicates a natural relationship.

Static electric fields

Static electric fields are produced by a number of man-made sources, as well as many natural phenomena. Electric charges in the atmosphere, for example, produce a static electric field with an intensity of about 0.15 kV/m (Chalmers, 1967; Barnes, 1986). Everyone has experienced static electricity as the electric shock felt after walking across a carpet and the ‘static cling’ that develops on a comb, brush, or on clothing. Other common natural sources of DC electric fields include weather phenomena such as storm clouds, blowing snow, and swirling dust clouds. In addition to transmission lines, man-made sources of electric fields include electrified railway systems and, although less common today, cathode ray tubes (CRT) in older computer and television picture screens.

A person’s static electric field exposure depends on the frequency with which he or she encounters these sources, as well as the distance from these sources. Static electric fields decrease rapidly with distance from their source. Furthermore, common objects (such as trees, fences, and buildings) block static electric fields, such that outside sources cannot be measured indoors.

Table 1 describes the typical static electric field levels associated with common sources. This table illustrates that 1) we are surrounded by natural sources of DC electric fields; and 2) static electric field levels associated with DC transmission lines are in the range of common sources.

Table 1. Typical static electric field levels from common natural and man-made sources

Source	Electric Field Level (kV/m)
Man-made Sources	
TV and CRT computer screens (at 30 centimetres)	10–20
Under a ±500-kV transmission line	20-30
Natural Sources	
Distant storm front	10-20
Storm cloud over a lake	40
Friction from walking across a carpet	Up to 100
Surface charge on the body from static cling	Up to 500

Source: Johnson, 1985; Barnes, 1986

Static magnetic fields

Just like static electric fields, static magnetic fields are produced by numerous man-made and natural sources. The most prevalent static magnetic field is that produced by the Earth as a result of constant flow of current deep within the Earth's outer core. This is called the Earth's geomagnetic field and it is this field that is used for compass navigation. The geomagnetic field ranges in intensity from 300-700 mG, varying at different latitudes. It is highest at the magnetic poles and lowest at the equator. The strength of this field in Manitoba is about 580 mG (NGDC, 2010). Depending on the orientation of a DC transmission line with respect to the magnetic field of the Earth, a DC transmission line can either add to or subtract from the strength of the Earth's geomagnetic field.

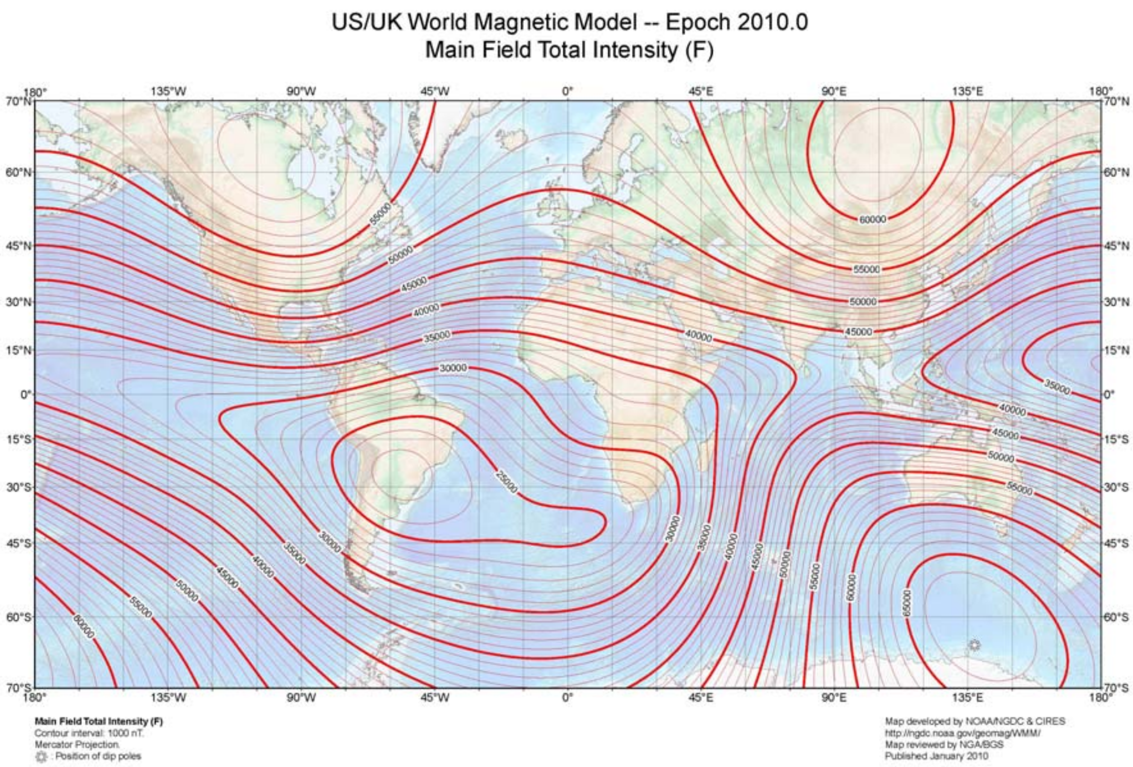

Figure 2. Map of the Earth's geomagnetic field (NOAA/NGDC, 2010)

DC magnetic fields are also created by ferromagnetic ore deposits. Iron and steel used in building construction and in vehicles are also sources of DC magnetic fields. In addition to transmission lines, man-made sources include devices that produce or use a steady flow of electricity (e.g., magnetic resonance imaging [MRI] machines, appliances using DC power from a battery, and permanent magnets).

Table 2 describes the typical static magnetic field levels measured near some of these sources. Similar to static electric fields, static magnetic fields decrease rapidly with distance from their source. This table illustrates that 1) we are surrounded by natural sources of DC magnetic fields and 2) static magnetic field levels associated with DC transmission lines are much lower than those produced by common sources. The static magnetic field levels from overhead DC transmission lines are similar to or less than levels of the surrounding geomagnetic field.

Table 2. Typical static magnetic field levels from common natural and man-made sources

Source	Magnetic Field Level (mG)
Man-made Sources	
Battery operated appliances	3,000 – 10,000
Electrified railways	< 10,000
MRI machines	15 million – 40 million
Under a ±500-kV HVDC transmission line operating at 2,000 Amperes	250-560
Natural Sources	
Earth's geomagnetic field in Manitoba	~ 580

Source: WHO, 2006

Corona phenomena

Corona refers to the partial electrical breakdown of the air into charged particles. These air ions are formed when the electric field at the surface of a conductor becomes large enough to dislodge one or more electrons from the air molecules in the immediate vicinity, usually within 2 to 3 centimetres (cm) of the conductor. Particles, dust, liquid droplets, and insects that deposit on a conductor "enhance" the electric field at its surface, thereby forming point sources of corona, and thus, sources of air ions. Corona occurs to a lesser degree when transmission line conductors are clean and smooth. Corona, therefore, is strongly affected by the environment, particularly weather conditions (humidity, temperature, and precipitation) and the season of the year. In fair weather, with little debris on the conductors, corona occurs to a lesser degree than in foul weather where the conductors have many droplets on them due to precipitation; however, all DC transmission lines in operation generally produce corona to some degree because of deposits on their surfaces.

Corona results in the generation of (+) or (-) air ions of the same polarity as the conductor producing corona.[4] Thus, a (+) conductor in corona acts as a source of (+) air ions, while a (-) conductor in corona acts as a source of (-) air ions. Since the voltage on DC conductors does not change polarity as it does on an AC transmission line, air ions of the same polarity as the

[4] Air ions with a net positive charge are called (+) ions; those with a net negative charge are called (-) ions.

conductor continuously move away from it to the opposing conductor or to the ground and are neutralized.[5]

The DC electric field primarily drives the electrically charged air ions toward the conductor of the opposite polarity or toward the ground, with a few being driven upward above the transmission line. Movements of air ions are also influenced by the wind.

The air ions from corona cause a space charge and the flow of charge through the air to the ground (i.e., ion current density). Figure 3 displays the relationship of corona and its various effects.

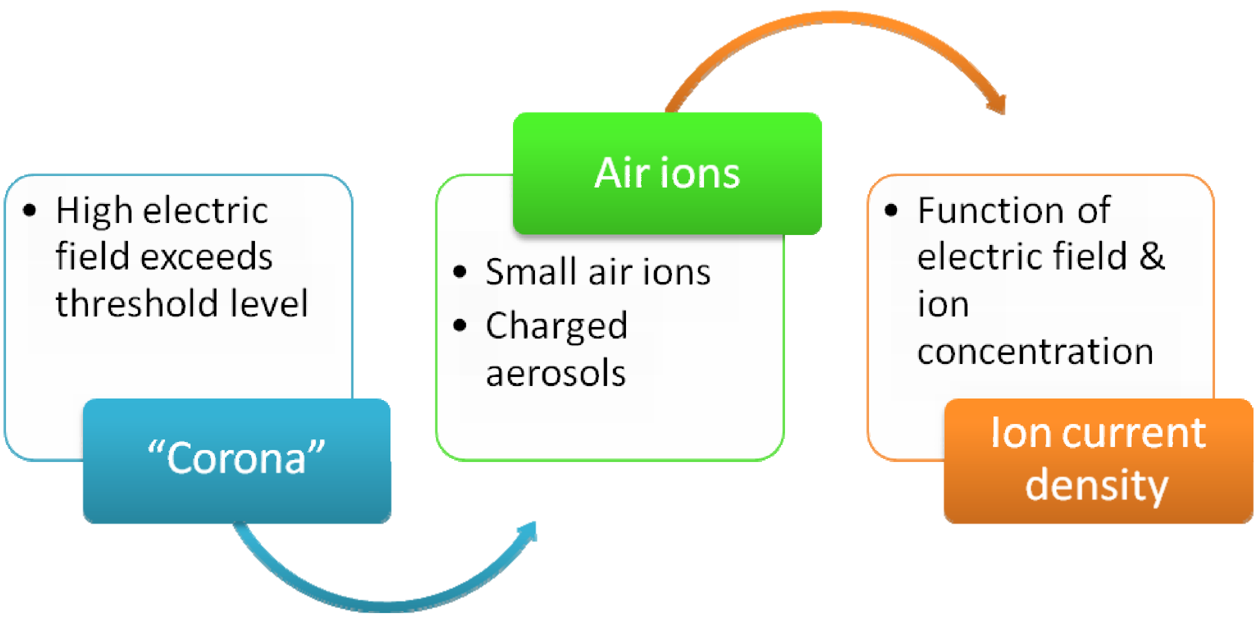

Figure 3. Relationship of corona-related phenomena

Space charge

Electrical charges in the air are formed by many common natural sources: by the Earth and its atmosphere, energy released by evaporation (i.e., the break-up of water droplets), friction from blowing snow and swirling dust, open flames and other combustion processes, and various meteorological events. Air ions in the atmosphere can be characterized by their size—small air

[5] When an AC transmission line is in corona, air ions formed in the process are alternately repelled and attracted as voltage polarity changes on the conductors at 60 Hz and so are rapidly neutralized.

ions or large air ions—and by their mobility. Collectively air ions and charged aerosols are referred to as space charge.

Small air ions

Air ions are atoms, molecules, or small clusters of atoms or molecules in the air that carry a net imbalance of one or more electrical charges. When an energy source displaces an electron from a neutral gas molecule, it is left with a net positive charge. The displaced electron is quickly captured by another gas molecule which causes that molecule to have a net negative charge if it was previously neutral (i.e., evenly balanced positive and negative charges). Small air ions have diameters of 1 to 10 nanometers (nm) and mobilities in the range of 0.2 to 2.5 x 10^{-4} metres square per volt per second ($m^2/V{\cdot}s$), with values of 1.4 and 1.8 x 10^{-4} $m^2/V{\cdot}s$ representing the average mobilities of (+) and (-) small air ions in dry air, respectively. Somewhat lower mobilities of (+) and (-) small air ions (1.15 and 1.5 x 10^{-4} m^2/V s, respectively) have been measured in natural outdoor conditions. When the excess electrical charge binding molecules together is neutralized, small air ions cease to exist.

As noted above, electrical charges in the air are formed by many common natural sources. Air ion concentrations depend strongly on atmospheric conditions, geographic location, and air quality. Typical air ion levels in clean, rural air are on the order of 500 to 2,000 air ions/cm^3 for (+) small air ions and slightly fewer for (-) small air ions. It is estimated that 10 pairs of (+) and (-) air ions are produced in each cubic cm of air every second (Kotaka, 1978). Higher concentrations (i.e., > 2,000 ions/cm^3) and lower concentrations of air ions (< 500 ions/cm^3) have also been reported (Anderson, 1971) due to the many common man-made and natural phenomena that can affect average levels. Table 3 illustrates the variability of air ions levels.

Table 3. Typical concentrations of air ions

Location or condition	Concentration of ions/cm^3
Fair weather, open spaces	500-2,000*
Fair weather, urban environment	
Manitoba	0 – 5,300†
Chicago	50 – 800
Air humidified by boiling water, e.g. from a tea kettle	1 million – 10 million‡
Basement family room	400-800*
Basement family room, candle lit	Up to 27,600*
Small waterfall, 200 feet	1,500 - 2000*
Beach with surf	3,000 - 7,000*
Bathroom with shower running	9,000†
Electric heating elements	10,000§
Highway, 20 feet (30 vehicles/minute)	6,900 - 15,000*
Vehicle exhaust, 5 feet	34,500 - 69,000*
Burning gas jets	100,000§
Burning match, 12 inches	200,000 - 300,000*

*Sources: *Johnson, 1982; †Exponent; ‡Carlon, 1980; §Anderson, 1971*

Charged aerosols

Small air ions are small clusters of gas molecules held together by charge. When the charge from air ions becomes attached to particles or aerosols in the atmosphere the aerosol are called 'charged aerosols.' Sometimes ions with electrical mobilities that overlap with charged aerosols are referred to as large ions. The diameters of charged aerosols are in the range of 20 to 200 nm. Aerosols continue to exist unaltered when they lose their charge.

A minor mechanism by which small air ions are neutralized is by attachment to aerosols. Hence, where aerosol concentrations are high, the concentration of small air ions is reduced. Although indoor levels of small air ions can be similar to outdoor levels, the generally higher levels of aerosols indoors reduce small air ion concentrations. Common indoor sources of aerosols include dust particles, mites, animal dander, cooking fumes, and smoke from cigarettes or cigars, among other things.

While measurements of aerosol concentrations are frequently reported by atmospheric scientists and other researchers, measurements of charged aerosols are collected infrequently. Data from one of the few studies that reported ambient measurements of charged aerosols is summarized in Table 4.

Table 4. Aerosol concentrations and rough estimates of singly charged aerosols 0.16-0.24 µm (% of total charged) in various locations

Location	Aerosol Count (aerosols/cm^3)	Fraction with 1 charge (%)
Race Point, MA	14,000	54
Marconi Beach, MA	4,000	39
El Capitan Beach, CA	9,000	51
Downtown Newark, NJ	83,000	46

Source: GE/DOE, 1989

The results of this study indicate that the reported smallest aerosols (0.16 micrometres [µm]) accounted for the highest fraction (%) of charged aerosols, while the reported largest aerosols (0.50 µm) accounted for the smallest fraction of charged aerosols. The fractions of smaller charged aerosols (0.16-0.24 µm) with single charges as a percent of all charged aerosols in this size range were estimated from figures in the GE/DOE report (1989). These measurements show that, despite a 10-fold difference in the concentrations of total (charged and uncharged) aerosols between clean ocean beach environments and a polluted urban environment, the fractions of charged aerosols with one charge were similar (39-54%) and the most common charge per particle was 0 or 1.

To further characterize background levels of charges on aerosols, Exponent engineers made measurements of aerosols and their charges at locations in Winnipeg, Manitoba and Chicago, Illinois. Table 5 displays the range of aerosol and charged aerosol concentrations measured in the Winnipeg and Chicago areas. Figure 3 summarizes the average percentages of all particles carrying charges at various outdoor settings.

Table 5. Range of levels of airborne aerosols (0.65 - 1 µm) carrying electrical charges (percent)

Location	Percent charged
Winnipeg	7 – 10
Chicago	7– 14

**Source: Bailey et al. (2011)*

These measurements of particles across a wide range of particle sizes show that the fraction of aerosols carrying charges is quite similar across a wide range of environments. As observed by the investigators who prepared the GE/DOE report (1989), the most common density of charges on aerosols at these sites was 0 or 1 charge per particle.

The data in Figure 4 provide greater detail on the data summarized in Table 5. However, the data in Figure 4 are not directly comparable to the data shown in Table 4 because Figure 4 shows the fraction of all aerosols that are charged up to 1.0 µm, whereas Table 4 displays the fraction of smaller aerosols as small as 0.16 µm with 1 charge. In addition, the ranges of aerosol electrical mobilities measured were not identical.

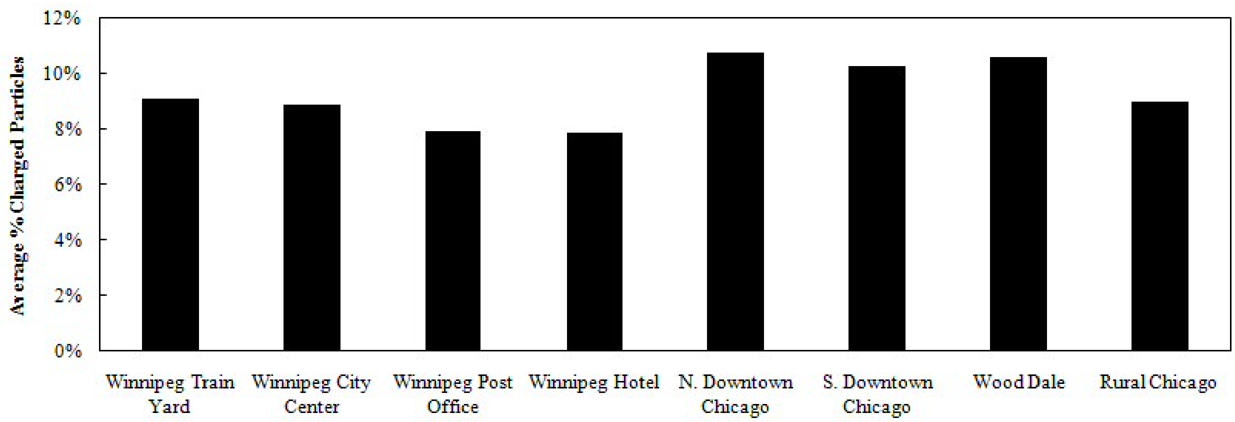

Figure 4. Fraction of all aerosols (0.65 µm – 1.00 µm) carrying charges in outdoor settings in the vicinity of Winnipeg, Manitoba and Chicago, Illinois.

Ion current density

Ion current density is a phenomenon that can be described as the flow of charge through the air to the ground (or to grounded objects including people), which is expressed in nanoamperes per square metre (nA/m^2). Ion current density is a function of the electric field and ion concentration. It is, therefore, of interest because it is a good predictor of surface charge, including the likelihood that the electric fields and ions can be perceived (i.e., felt by the movement of hair on the head or arms).

Air quality

In addition to the production of air ions, corona on DC and AC transmission lines also can lead to the production of trace quantities of ozone (O_3). During corona, electrons from the conductor surface strike neutral gas atoms in the air which may then divide into an electron and a (+) ion. The electrons are accelerated in the electric field from the conductor and may collide with neutral oxygen molecules to cause them to disassociate into two negatively charged oxygen atoms. Ozone is formed when single negative oxygen atoms react with neutral oxygen molecules.

Other natural and man-made sources of ozone include sunlight and fuel combustion from cars, trucks, and factories. Ozone is normally present in the atmosphere in rural areas of Manitoba at levels of about 20-22 parts per billion (ppb) (Environment Canada, 2008). As a result of research showing that ozone at high levels can harm lung function and irritate the respiratory system, the maximum acceptable levels for ozone established by the Canadian National Ambient Air Quality Objectives is 82 ppb (1 hour basis) for O_3 (Health Canada, 2006).

An early study of a ±500-kV DC test line only sporadically detected O_3 downwind of the conductors in wet weather (Droppo, 1979). The most comprehensive study to date performed 2.5 years of pollutant and weather monitoring before and after the construction of a ±400-kV transmission line in Minnesota. While pollutants were detected in some cases, "the increments above the background levels were very small and near the detection limits and noise levels of the monitoring equipment." Turning the transmission line on and off did not result in detectable changes in the concentration of pollutants. An increase was only detected when downwind values were compared to upwind measurements (Krupa and Pratt, 1982). Measurements on a ±450-kV DC test line in Québec did not show a relationship between corona losses on the line and O_3 levels measured downwind (Varfalvy et al., 1985).

Thus, there is no theoretical basis or empirical data to suggest that a DC transmission line would significantly increase background levels of O_3 and adversely impact ambient air quality. As a result, air quality is not evaluated further in this report.

Audible noise

AN results from the partial electrical breakdown of the air around the conductors of a transmission line. In a small volume near the surface of the conductors, energy and heat are dissipated. Part of this energy is in the form of small local pressure changes, which cause AN in the form of a hissing, crackling, or popping sound.

The conductors of transmission lines are designed to be free of AN under ideal conditions. Protrusions on the conductor surface (particularly water droplets on or dripping off the conductors or other debris that settles on the conductors), however, can cause electric fields near the conductor surface to exceed the levels that cause breakdown of the insulating properties of the air. The partial electrical breakdown of the air around the conductors of an overhead transmission line produces a dissipation of energy and heat in a small volume near the conductor surface that changes the sound pressure in the surrounding air. If this small local pressure change exceeds ambient background levels it may be perceived as AN. DC transmission lines do not generate substantial AN during fair weather and during foul weather (wet conductors) AN is attenuated. AN levels are lowered in foul weather (rain or other precipitation) due to the large increase in ions from the line, an increase caused by the precipitation drops acting as corona points. The increase in ion density around the line enlarges the effective size of the conductor and thus lowers AN levels (e.g., larger conductors = lower AN levels). Wet conductors can occur during periods of rain, fog, snow, or ice.

The amplitude of a sound wave is the incremental pressure difference resulting from sound in relation to atmospheric pressure. The sound-pressure level is the fundamental measure of AN; it is generally measured on a logarithmic scale with respect to a reference pressure. The sound-pressure level (SPL) in decibels (dB) is:

$$SPLdB = 20 \log10 (P/P0)$$

where P is the effective root mean square (rms) sound pressure and P0 is the reference pressure of 20 micropascals (μPa), the approximate threshold of human hearing. The human auditory response depends on frequency, with the most sensitive range roughly between 2,000 and 4,000 Hz. The frequency-dependent sensitivity is reflected in various weighting scales for measuring AN. The capability to detect noise from the line at residential dwellings was evaluated by calculating the AN in dB on the A-weighted scale (dB-A). The A-weighted scale weights the various frequency components of a noise in approximately the same way that the human ear responds.

Table 6. Examples of audible noise levels

Sound Pressure	dB-A	Condition
	140	
100 Pa	134	Threshold of Pain
	130	
		Pneumatic Wood Chipper; Jackhammer
	120	
10 Pa	114	Loud Auto Horn (~ 3'); Rock Concert
	110	
	100	
1 Pa	94	Inside Subway Train (NY)
	90	
		Inside Bus
	80	
100 milli-Pa	74	Traffic on Street Corner
	70	
		Conversational Speech
	60	
10 milli-Pa	54	Typical Business Office
	50	
		Suburban Living Room
	40	
1 milli-Pa	34	Quiet Library
	30	
		Quiet Bedroom at Night
	20	
100 micro-Pa	14	Broadcast Studio
	10	
20 micro-Pa	0	Threshold of Hearing

Radio noise

Corona caused by high electric field levels at the conductor surface induces impulsive currents along a transmission line. These induced currents, in turn, cause wideband electric and magnetic noise fields that can affect radio and television reception. This is experienced as 'static' interference with reception of radio signals in the amplitude-modulated (AM) broadcast band from 535 kHz to 1.605 megahertz (MHz) and, to a lesser extent, television signals in the very-high-frequency (VHF) band from 54 to 88 MHz. The wideband RN from the proposed Bipole III transmission line can be expected to affect reception under and close to the line, depending on the broadcast station's signal strength. Digital television signals and satellite radio signals are not susceptible to this source of interference. Radio reception in the frequency-modulated (FM) broadcast band from 88 to 108 MHz is rarely affected. The severity of RN is a function of the signal strength, noise level, and signal-to-noise ratio and therefore is greatest close to the line and far from the broadcast antenna.

Like AN levels, RN levels are lowered in foul weather (rain or other precipitation) due to the large increase in ions from the line, an increase caused by the precipitation drops acting as corona points.

Scientific Reviews and Guidelines

Researchers have been investigating the possible health effects of static electric and magnetic fields for a very long time. Magnetic fields have been studied more than electric fields because conducting objects, such as trees and houses, shield electric fields. There has been considerably less research on long-term health effects (like cancer) and DC magnetic fields compared to the body of research on AC magnetic fields. This is because static magnetic fields do not induce currents in stationary objects (such as people or animals). Currents are only induced when there is motion in the static magnetic field. This type of current induction, however, is not a concern at the very low levels of magnetic fields produced by the Earth or by DC transmission lines.

The body of research on static fields consists largely of studies on the short-term effects (e.g., perception and shocks) of very strong static fields. Research on long-term effects includes epidemiology studies of workers exposed to static magnetic fields, surveys of residents living near DC lines, animal studies, and studies in cells and tissues. The best way to understand all of this research is to rely on the conclusions of the numerous, independent scientific panels that have evaluated this research using a scientific approach.

Over the past 25 years, there have been a number of reviews of the scientific literature on static fields by scientific or regulatory organizations. These have included evaluations performed by the American Conference of Governmental Industrial Hygienists (ACGIH), Health Canada, the International Agency for Research on Cancer (IARC), the International Commission on Non-ionizing Radiation Protection (ICNIRP), the International Committee on Electromagnetic Safety (ICES), the Minnesota Environmental Quality Board (MEQB), the National Radiological Protection Board (NRPB), the U.S. Food and Drug Administration (FDA), and the World Health Organization (WHO). The NRPB also reviewed research related to air ions and the MEQB reviewed the research on air ions and charged aerosols. Figure 5 provides a timeline of these scientific reviews performed between 2000 and 2010. These reviews, guidelines, and standards serve as criteria for the assessment of the DC electric and magnetic fields associated with the proposed project.

In summary, these reviews concluded that experimental studies have established acute sensory responses associated with high static electric and magnetic fields. Static electric fields can be directly perceived causing annoyance effects and can also indirectly cause electrostatic discharge. High static magnetic field levels can lead to non-life threatening effects such as vertigo, nausea, and visual sensations (phosphenes). Research related to long-term health effects (i.e., cancer) has focused on prolonged exposure to high field levels (e.g., exposures of MRI operators), although the available evidence is inadequate to draw any conclusions at this time. This research is not relevant to the levels of the very weak static electric and magnetic fields associated with DC transmission lines.

Some organizations have recommended guidelines to limit human exposure to static electric and magnetic fields because of the acute effects described above. The exposure limits for static magnetic fields, however, are hundreds to thousands of times higher than the static magnetic field levels associated with DC transmission lines and other common sources. The proposed guidelines for static electric fields are closer in strength to the levels associated with DC transmission lines.

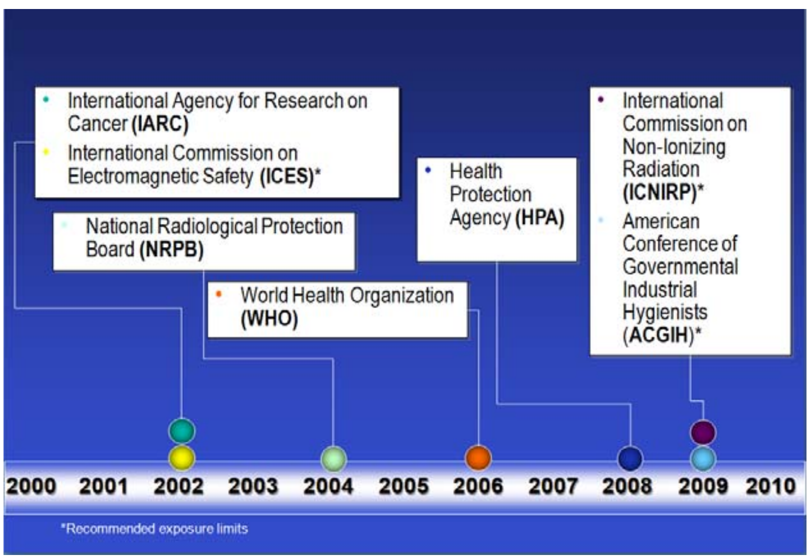

Figure 5. Timeline of major scientific organizations reviewing research related to static magnetic and electric fields since 2000

In addition to these reviews and standards related to static electric and magnetic fields, the MEQB and the NRPB have reviewed and assessed research related to small air ions and charged aerosols. To update the research on small air ions and charged aerosols for the current topics of interest, a review of individual research studies was performed to form a basis for conclusions in this area and is included as Appendix 2.

American Conference of Governmental Industrial Hygienists

The ACGIH routinely develops guidelines to assist in controlling exposures to potential health hazards in the workplace. The guidelines are designed to "... provide guidance on the levels of exposure and conditions under which it is believed that nearly all healthy workers may be repeatedly exposed, day after day, without adverse health effects" (ACGIH, 2009, p. 1).

The ACGIH did not conclude that exposure to static fields poses a serious health risk (ACGIH, 2009). Its guidelines are based on limiting currents on the body surface (static electric fields) and induced internal currents (static magnetic fields) to levels below those believed to produce adverse health effects. For static magnetic fields in the general workplace, whole body exposure should not exceed 2 Tesla (T) (20,000 G); for trained workers in controlled work environments, whole body exposures up to 8 T (80,000 G) are permitted on a daily basis. A higher exposure limit of 20 T (200,000 G) is permitted for the limbs. A magnetic flux density of 20,000 G is recommended as an overall ceiling value. For static electric fields, the ACGIH found no convincing evidence that occupational exposure leads to adverse health effects, but recommended a rms Threshold Limit Value of 25 kV/m (peak = 35 kV/m) to minimize annoyance from surface fields and nuisance shocks (in dry weather).

Health Canada

Health Canada has published guidelines on short-term exposures of patients and continuous long-term exposure of operators to the strong static magnetic fields of MRI devices, at 2 T (20,000 G) and 0.01 T (100 G), respectively (Health Canada, 1987). The panel of scientists assembled by Health Canada concluded: "On the basis of a number of carefully performed studies, the following important biological processes appear not to be affected by static magnetic fields up to approximately 2 T [20,000 G]: (1) cell growth and morphology, (2) DNA structure and gene expression, (3) reproduction and development, (4) bioelectric properties of isolated neurons, (5) animal behaviour, (6) visual response to photic stimulation, (7) cardiovascular dynamics, (8) hematological indices, (9) immune response, (10) physiological regulation and circadian rhythms" (p. 7).

International Agency for Research on Cancer

IARC, the world's authority on cancer, concluded that the evidence does not support a cause-and-effect relationship between static magnetic fields or static electric fields and cancer. The IARC Working Group classified static fields in "Group 3-Not Classifiable" because of inadequate evidence from either human or animal studies that such exposures cause or contribute to cancer. IARC defines "inadequate evidence of carcinogenicity" as "The studies cannot be interpreted as showing either the presence or absence of a carcinogenic effect because of major qualitative or quantitative limitations, or no data on cancer in experimental animals are available." As the WHO later noted, the uncertainty about long-term exposure pertains to static magnetic fields in the millitesla (mT) range (WHO, 2006a), but not in the range of the Earth's geomagnetic field or the range of fields produced by DC transmission lines similar to the proposed Bipole III project.

International Commission on Non-Ionizing Radiation Protection

Guidelines on static magnetic fields have been proposed by ICNIRP (ICNIRP, 2009). ICNIRP was established as a continuation of the former International Non-Ionizing Radiation Committee of the International Radiation Protection Association. The ICNIRP directive is to investigate hazards that may result from non-ionizing radiation and to protect the public. Their 2004 guideline allowed for the continuous average exposure of the general public to static magnetic fields at levels below 40 mT (40,000 µT). The NRPB supported these guidelines as a "cautious approach" (NRPB, 2004b, p. 137). In 2009, ICNIRP increased the limit on public exposure to static magnetic fields 10-fold to 400 mT (i.e., 400,000 µT [4,000 G]). The effects of concern at exposures above the limit are induced flow potentials in large blood vessels and vertigo or other sensory responses caused by currents induced by rapid movements in the field.

International Committee on Electromagnetic Safety

ICES has published an IEEE standard for AC magnetic fields up to 3 kilohertz (kHz) and magnetic fields at near static frequencies (< 0.153 Hz). The standard is focused on preventing adverse biological effects from short-term exposures, since the evidence for long-term effects was not sufficient or reliable.

It is instructive to compare the standards developed by ICNIRP and ICES for static magnetic fields to the standards for 60-Hz magnetic fields. Table 7 compares magnetic-field guidelines from ICNIRP and ICES (ICES, 2002; ICNIRP, 2009; ICNIRP, 2010).

Table 7. Comparison of screening guidelines for public exposure to DC and 60-Hz AC magnetic fields

	ICNIRP		ICES	
Frequency	AC	DC	AC	DC[6]
Magnetic Field (mG)	2,000 mG*	4,000,000 mG†	9,040 mG‡	1,118,000 mG§

*200 µT; † 400 mT; ‡904 µT; §111.8 mT

This table illustrates that DC magnetic-field exposure standards are far higher than for AC magnetic fields. As explained in these standards, the differences between these guidelines for DC and AC magnetic fields relates to the basic differences in the way these fields interact with organisms.

ICNIRP (2009) recommended special consideration for static magnetic field exposures of individuals with cardiac pacemakers and other electronic medical devices and ferromagnetic implants, but noted that no adverse effects are expected at exposure levels below 0.5 mT (5 G).

Minnesota Environmental Quality Board

A multidisciplinary panel of seven scientists (Science Advisors) convened by the MEQB prepared a critical review of the scientific and medical studies relating to the possible biological effects of the electrical environment of DC transmission lines (MEQB, 1982). Six of these scientists concluded that the literature analyzed up to the date of their review did not provide a scientific basis to conclude that electric fields, magnetic fields, or air ions pose a hazard to human or animal health. The seventh scientist agreed that no proof of adverse effects had been found in the review, but stated that, given some uncertainties in the data, the possibility of effects of air ions should not be dismissed without further research. A subsequent review of additional research data and studies by the Science Advisors did not change the earlier conclusion (MEQB, 1986).

[6] Spatial maximum for frequencies < 0.153 Hz.

National Radiological Protection Board

The NRPB, now a division within the Health Protection Agency of Great Britain, has a long history of providing support and advice on public health issues relating to ionizing radiation and electromagnetic fields to the National Health Service, the Department of Health, and other government bodies in the United Kingdom. The NRPB has issued reviews and assessments on static electric and magnetic fields and charged aerosols.

In 2004, the NRPB published a comprehensive review of epidemiologic and biological studies and physical mechanisms of interactions of static electric and magnetic fields and made recommendations for restricting time-averaged occupational exposures to static magnetic fields to 200 mT (2,000 G) and the general public's exposure to 40 mT (400 G) (NRPB, 2004b). These restrictions are similar to but slightly lower than the guidelines recommended by ICNIRP. This review and assessment of the magnetic field research was updated in 2008 (HPA, 2008). The overall conclusion was:

> At levels of static magnetic field exposure above about 2 T[esla], [20,000 G] transient sensory effects occur in some individuals; these effects relate at least in part to movement in the field. No serious or permanent health effects have been found from human exposures up to 8 T [80,000 G], but scientific investigation has been very limited. The effects of human exposure to fields above 8 T [80,000 G] are unknown, but some cardiovascular and sensory effects would be expected to increase with stronger fields (p. 3).

The NRPB did not recommend a formal limit on static electric field exposures but noted that annoying sensations (surface charge perception on body hair) can occur above 25 kV/m (relevant only to dry weather conditions).

Research on air ions and charged aerosols has also been reviewed by the NRPB. A group of scientists was assembled to provide input to the Advisory Group on Non-Ionising Radiation (AGNIR) of the NRPB on the possible effects of corona ions or electric fields on exposure to airborne pollutants and to address the question of whether corona ions increase the dose of pollutants to target tissues in the body (NRPB, 2004a). AGNIR examined the hypothesis that a sufficient amount of charge can attach to pollutant aerosols and increase deposition of the aerosols. The conclusion of AGNIR was that "the additional charges on particles downwind of power lines could also lead to deposition on exposed skin. However, any increase in deposition is likely to be much smaller than increases caused by wind." Their conclusion identified uncertainties about the inhalation of charged particles, but stated, "However, it seems unlikely that corona ions would have more than a small effect on the long-term health risks associated with particulate pollutants, even in the individuals who are most affected. In public health terms, the proportionate impact will be even lower because only a small fraction of the general population live or work close to sources of corona ions" (AGNIR, 2004, p. 48). This assessment has been reaffirmed by the WHO (2007).

A comprehensive review of available research on air ions and respiratory, mood, and behavioral effects is summarized in Appendix 2 to provide a basis for conclusions in this area. This review of human exposures to space charge does not suggest effects on the respiratory system, including those of sensitive persons, and reports of mood-elevation by space charge only have some support at levels about 10- to 30-fold greater than the levels found under transmission lines, and cannot easily be distinguished from placebo effects.

U.S. Food and Drug Administration

The FDA's Center for Devices and Radiological Health has issued guidance to manufacturers submitting 510 (k) applications for review of MRI diagnostic devices in accordance with 21 CFR 807.87 (FDA, 1998). Per that guidance, exposure up to 4 T (40,000 G) from MRI devices is not considered a significant risk to patients. This guidance document also recommends that manufacturers of MRI systems producing a rate of change of the magnetic field (dB/dt) greater than 20 T/second (200,000 G/second) study and warn operators about dB/dt levels that can induce peripheral nerve excitation. A labeling guideline is also required for areas surrounding MRI devices where persons with cardiac pacemakers may be exposed to static magnetic fields exceeding 0.5 mT (5 G). This guideline is designed to protect against strong attractions of ferromagnetic materials to the device's magnet. They also recommended that access be controlled in areas where magnetic field exposure may result in a potential dysfunction of ferromagnetic medical implants and electronic medical devices. Evaluations of medical devices other than MRI devices that produce electromagnetic fields are not assessed with respect to formally established guidelines, but are assessed on a case-by-case basis. The FDA concluded that MRI diagnostic devices that emit static magnetic field levels *greater* than 4 T (40,000 G) for neonates and 8 T (80,000 G) for adults, children, and infants aged > 1 month are considered to pose significant risk (FDA, 2003). These risk assessment levels are based on clinical studies in which no significant short-term or persisting effects of exposures to static magnetic fields up to 8 T were reported.

World Health Organization

The WHO has published a comprehensive review of possible health and biological effects of static fields as an Environmental Health Criteria report (WHO, 2006b). The conclusions were:

> Short-term exposure to static magnetic fields in the tesla range [i.e., above 10,000 G] and associated field gradients revealed a number of acute effects (p. 216).
>
> With regard to static magnetic fields, the available evidence from epidemiological and laboratory studies is not sufficient to draw any conclusions about chronic and delayed effects. IARC (2002) concluded that there was inadequate evidence in humans for the carcinogenicity of static magnetic fields, and no relevant data available from experimental animals. They are therefore not at present classifiable as to their carcinogenicity to humans (p. 216).

This conclusion is the same as the earlier IARC (2002) report regarding DC magnetic fields, but the context for these conclusions is clearer in the WHO document. The range of exposure for which the WHO identified uncertainty and an insufficiency of evidence is above 0.01 T (100 G) and, for this reason, the WHO recommended additional research at higher exposure levels. The WHO further recommended cost-effective precautionary measures that would apply to high field exposures resulting from the industrial and scientific use of DC magnetic fields (WHO, 2006a; 2006b). An independent review performed for the European Commission by the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) also concluded that risk assessments are only necessary with respect to very high occupational exposures to DC magnetic fields, e.g., from MRI devices (SCENIHR, 2007). The conclusions of this 2007 review were re-affirmed in an updated opinion by this scientific panel (SCENIHR, 2009).

In their discussion of studies on the effects of static electric field in animals, the WHO concluded "No evidence of adverse health effects have been noted, other than those associated with the perception of the surface electric charge" (WHO, 2006b, p. 5). The WHO also noted that the IARC had not identified any studies of long-term exposure to static electric fields from which any conclusions on chronic or delayed effects could be made, which rendered the evidence insufficient to determine the potential carcinogenicity of static electric fields. On the whole, the WHO concluded that "the only adverse acute health effects [related to static electric fields] are associated with direct perception of fields and discomfort from microshocks" (WHO, 2006b, p. 8).

Electrical Environment of Bipole III – Static Fields

Electricity on a DC transmission line is carried over two conductor bundles or 'poles' supported above the ground by insulators suspended on either side of a steel tower. The proposed Bipole III transmission line will utilize two types of towers. In the northern part of the route, the transmission line will be constructed on guyed towers in forested areas and other areas that are compatible with the use of this tower type. In the southern half of the route, through agricultural areas, the transmission line will be constructed on self-supporting lattice towers. Since the electrical effects associated with each section of the line are very similar, unless noted otherwise, all references to electrical parameters will be to calculated values for the line on lattice towers with typical operating conditions and load. All calculated values referenced in this section are based upon extensive modeling of the proposed Bipole III transmission line (Appendix 1). For comparison, the electrical environment of the existing Bipole I and II transmission lines are also presented in Appendix 1.

The proposed Bipole III transmission line will operate at a constant voltage of ± 500 kV, i.e., the poles will maintain a (+) or (–) potential with respect to the ground of 500 kV. The maximum current flow on the Bipole III line typically will be 2,000 amperes (A) when serving a 2,000 megawatt (MW) load.

DC electric field

Each of the poles is a source of a DC electric field, which is identical in nature to naturally-occurring static fields. The intensity of the electric field is greatest at the conductor surface and decreases rapidly with distance to the ground. During fair weather, the median electric field underneath the line will be about 22 kV/m and will increase in foul weather to 30 kV/m. At the edges of the ROW, the field levels will be much lower in fair (6.5 kV/m) and foul (9.3 kV/m) weather. During all weather conditions, the electric field decreases sharply with increased distance from the line. Based on historical weather records for 1990-2004, fair weather prevails more than 80 percent of the time in Winnipeg and The Pas, but only about 70 percent of the time further north in Thompson (personal communication. Z. Kieloch). The range of field levels encountered by the public will be well within the range of commonly encountered background levels of static electric fields.

The potential direct interaction of DC electric fields with humans, animals, and the environment is limited to the movement of surface charges on the surface of the body; the field does not enter the body (IARC, 2002). This conclusion is supported by studies of humans and animals exposed to a wide range of field strengths over varying periods for which no consistent behavioral or physiological responses are noted except those related to field perception. At sufficiently high levels, an electric field can be sensed by the movement of body hair. A psychophysical study of the ability of human subjects under carefully controlled conditions to detect a static electric field reported a range of perception thresholds, but the average critical detection value was 40.1 kV/m. When the ion current density was simultaneously raised to 120 nA/m^2 (1.33 x 10^5 $ions/cm^3$), the threshold was lowered to 25 kV/m (Blondin et al., 1996). Testing done outdoors under DC transmission lines indicates that most persons would not detect electric fields at levels less than about 25 kV/m (Clairmont et al., 1989; NRPB, 2004a).

As described above, the NRPB has recommended 25 kV/m as the general public limit for DC electric fields (NRPB, 1994). A similar value has been recommended as a Threshold Limit Value for occupational exposures (ACGIH, 2009). A higher value of 42 kV/m was recommended as an upper limit (basic restriction) in an earlier Comité Européen de Normalisation Électrotechnique pre-standard (CENELEC, 1995).

In fair weather, the calculated DC electric fields of Bipole III will be below the lowest recommended limit of 25 kV/m. In foul weather, in which persons are less likely to be on the ROW, the DC electric fields may exceed this value within portions of the ROW, although the likelihood of field perception would not expected to be increased because perception results from the movement of hair on the head and body and the body surface would likely either be covered by clothing or wet during foul weather.

Unlike AC electric fields, DC electric fields are not capable of coupling effectively to conductive objects and so the current density intercepted by a person under a DC transmission line is on the order of a few microamperes, which is below the threshold for detection of DC currents. Even for large vehicles parked underneath a DC transmission line or long parallel fences, the charge collected is limited by leakage current to the ground so the possibility of perception is limited; under experimental 'worst case' conditions, the only noticeable effect of touching a large, well grounded vehicle would be a microshock, weaker than what a person might experience after shuffling across a carpet. This finding has been confirmed for Bipole I and II (Maruvada et al.,

1982) and DC test lines (EPRI, 1978).

DC magnetic field

The magnetic field that will be produced by the proposed Bipole III transmission line is identical to the geomagnetic field of the Earth. The strength of this natural field in Manitoba is about 580 mG. Since magnetic fields are vectors, the magnetic field from the line will add to that of the Earth's geomagnetic field when the vectors are pointing in the same direction, and it will partially cancel the Earth's geomagnetic field where the magnetic field vectors of the DC lines point in the opposite direction. The result is that the measured magnetic field will be increased above background levels on one side of the ROW and will be decreased below background levels on the other side of the ROW. Outside the ROW, there will be an insignificant change in the background geomagnetic field. The contribution of the transmission line to this background field will be less than 405 mG in bipolar or monopolar operation even under the heaviest expected normal load.

Biological and health studies involving exposure of humans and multiple species to DC magnetic fields have been performed for over one hundred years. Evaluations of this research have been commissioned by a number of scientific agencies. These reviews and the resulting standards are described in detail in the section Scientific Reviews and Guidelines above. The ICNIRP has published reviews of biological effects and mechanisms (Matthes et al., 1997, 2000). The IARC concluded that the data did not deserve classification as a potential carcinogen and described static magnetic fields as not classifiable (Group 3) (IARC, 2002). Based on a review that included more recent studies of human subjects exposed to strong static magnetic fields from MRI devices and an evaluation of known mechanisms of interaction, ICNIRP recommended that the maximum exposure of the general public be increased from 40 mT to 400 mT, which is equivalent to 4,000 G (ICNIRP, 2009). Health Canada has published guidelines on short-term exposures of patients and continuous long-term exposure of operators to the strong static magnetic fields of MRI devices, at 2 T (20,000 G) and 0.01 T (100 G) respectively. Both the Earth's geomagnetic field and the magnetic field from the proposed Bipole III transmission line are hundreds to thousands of times lower than these limits.

Electrical Environment of Bipole III – Space Charge

Air ions

A transmission line is "in corona" when the strength of the electric field at the conductor surface exceeds a threshold or onset level of approximately 30 kV/cm. The calculated electric field gradient along the span of the proposed Bipole III conductors is below the threshold for corona onset (i.e., approximately 22.4 kV/cm); however, the presence of minor imperfections in the conductor surface (i.e., nicks, scratches, dust contamination, insect contamination, and ice, snow, or water droplets) can cause the electric field to be concentrated at these points and exceed this threshold producing corona. The energy released by corona discharge can lead to air ions.

Air ions around DC transmission lines have been well characterized by measurement and calculations. Appendix 1 describes the air ion levels expected from the proposed transmission line. Corona discharge on the Bipole III line conductors will produce varying levels of small air ions at the ground that are highest under the conductors and lower at the edges of the ROW. The rapid reduction in ion concentration is explained by the movement of the ions of one polarity to the opposite conductor and to the ground by the electric field where the charge is neutralized. Outside the ROW, the electric field is much weaker and so the transport of the ions by wind tends to disperse the ions higher in the air rather than force them to the ground. When the wind blows strongly across the transmission line, the shape of the air ion and electric field distributions will be shifted, reducing values on the upwind side and increasing values on the downwind side. The calculated median level of air ions at the edge of the ROW is 20,000 ions/cm^3 or less, with lower values in fair weather. These values are higher than ambient background levels measured outdoors but within the range of exposures encountered from common sources (Table 8).

Table 8. Comparison of air ion levels from the proposed project to other sources

Conditions*	Ions/cm^3
Air humidified by boiling water, e.g., from a tea kettle†	1,000,000 – 10,000,000
In large towns	Up to 80,000
In a candle lit room	Up to 27,600
Near an open flame	200,000 – 300,000
200 feet from a small waterfall	1,500 – 2,000
20 feet from a highway (30 vehicles/minute)	6,900 – 15,000
5 feet downwind of vehicle exhaust	34,500 – 69,000
4 feet from a negative ion generator	26,000 (-)
Peak on the ROW	97,100‡
At the edge of the ROW (33 m from the centerline)	12,600 – 16,300‡

**Data from Johnson, 1982; †data from Carlon, 1980; ‡fair weather median*

No scientific or regulatory agency has determined that air ions pose a threat to the environment or health. As a result, no exposure guidelines have been proposed and no standards or guidelines exist as a criterion for comparison. The only guidelines for air ions are published by the Ministry of Health of the Russian Federation (MHRF) for maintenance of optimal levels in indoor environments, i.e., maintaining levels of air ions at or above levels in clean outdoor air, because *low* levels of air ions in buildings have been alleged as symptomatic of poor indoor air quality. The MHRF has recommended that (+) and (-) air ion levels be maintained in a building between a minimum level of 400 ions/cm^3 and a maximum level of 50,000 ions/cm^3 for public and industrial quarters (MHRF, 2003). The basis for the guideline was not described. The levels of air ions on the ROW exceed this range, but fall well within this range outside the ROW.

Charged aerosols

One process which eliminates air ions is the transfer of charge to ambient airborne aerosols. Few measurements of charged aerosols, including around DC transmission lines, have been published and methods for calculating expected levels have not been perfected. Carter and Johnson (1988) measured charged aerosol concentrations at 70 m, 150 m, and 300 m downwind of a ±500-kV monopolar test line in fair weather by measuring the charge concentration within a wire cage (small air ions were excluded by a potential on the cage). The level was highest at 70 m downwind and was markedly reduced at 150 m and 300 m. To estimate an upper limit on aerosol charging, Johnson and colleagues subsequently took measurements around a test line designed to produce ion levels two to three times greater than a typical DC transmission line. They found that the distribution of charges was bipolar with a slight predominance of (-) charges out to 200 m downwind. The most common number of charges (i.e., charges/aerosol) was a single charge. Carter and Johnson also took spot measurements downwind of the Pacific Intertie ±500-kV transmission line in California, which showed similar results (GE/DOE, 1989). Overall, while a small effect of these DC sources could be measured, the fraction of aerosols with charges was similar to, but sometimes slightly higher or lower, than measured in other environments (Table 4).

To obtain additional information about the effect of DC transmission lines on charged aerosol levels, Exponent engineers made measurements in rural Manitoba around the corridor on which the Bipole I (±450-kV) and Bipole II (±500-kV) DC transmission lines operate (Bailey et al., 2011). These lines are separated by about 65 m. The results are shown in Figure 6.

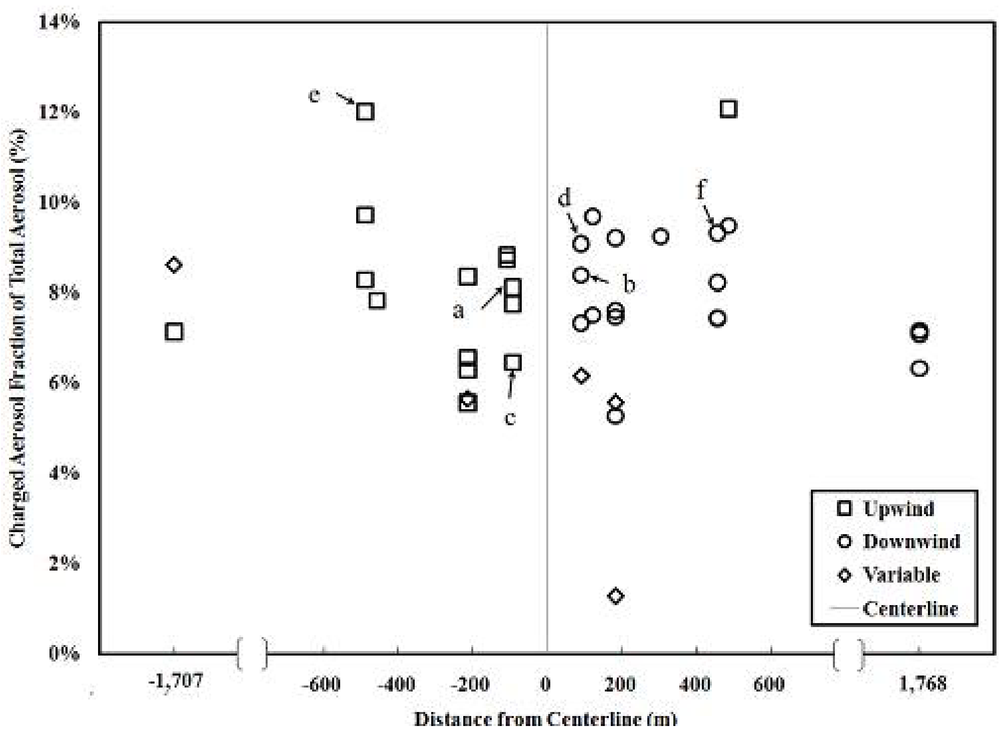

Figure 6. Charged aerosol fraction (%) with respect to distance from the centerline of the ±450-kV and ±500-kV transmission lines in Manitoba

The fractions of aerosols carrying (+) and (-) charges with selected mobilities within the range of 4.14 x 10^{-7} $m^2/V\cdot s$ and 9.64 x 10^{-10} $m^2/V\cdot s$ were measured at sites upwind and downwind of the lines. Measurements made at times when the wind was blowing from both directions during the measurement period (labeled "variable") are also shown. The average fractions of particles with charges within 500 m from the centerline were 5-10% at downwind locations, 6-12% at upwind locations, and 1-6% at locations when the wind direction varied. The fractions of charged aerosols at this site are similar to measurements taken at a variety of locations at a distance from a DC transmission line, as previously shown in Figure 4, and also commonly carried 0 or 1 charge per particle.

More detailed analyses were carried out on the distribution of charge on aerosols measured around the Bipole I and II transmission lines and the results are shown in Bailey et al. (2011). In summary, the fractions of aerosols carrying charge upwind and downwind were similar but the polarity of the charges downwind was shifted. Upwind the charges on aerosols were about equally likely to be (+) or (-), but downwind the number of aerosols with (+) charge was reduced relative to those carrying (-) charges. Slightly more aerosols with multiple charges were observed 90 m downwind than 90 m upwind and this difference appeared less at 490 m downwind. Nevertheless, both upwind and downwind of the lines the modal distribution was one charge per aerosol and almost all aerosols carried 10 or few charges. The number of charges on aerosols measured around the DC lines was very similar to that measured at four locations around Winnipeg and four locations around Chicago.

The data provide no indication that the two DC transmission lines in Manitoba substantially increase the number of aerosols bearing charges over background levels. Furthermore, neither the measurements made around Bipole I and II nor the measurements of test lines (GE/DOE, 1989) suggest that DC transmission lines lead to many more aerosols with a large number of charges per particle. Thus, the levels of charged aerosols around DC transmission lines do not appear to differ in any meaningful way from other ambient environments.

Electrical Environment of Bipole III – Audible Noise and Radio Noise

Additional corona phenomena

The energy released by corona discharge can also lead to AN, RN, and visible light. Appendix 1 describes the AN and RN levels expected from the proposed DC transmission line.

Audible noise

The median AN level on the ROW in fair weather is 39 dB-A and this diminishes to about 36 dB-A at the edge of the ROW. These values are within the range of values expected in quiet rural and suburban areas.

Manitoba's Provincial Guidelines specify maximum desirable 1-hour equivalent noise levels for both residential and commercial areas of 55 dB-A and 45 dB-A, for day-time and night-time periods, respectively (EMD, 1992). These standards will be met by Bipole III in fair weather even under the conductors on the ROW. In foul weather, the levels of AN will be about 6 dB-A lower and will typically be masked by noise from wind and rain.

Radio noise

The Industry Canada standard for RN for a 500-kV transmission line is 60 dBμV/m at 15 m from the nearest conductor that would be measured by a CISPR-type measuring instrument according to CSA Standard C108.1.1-1977 (Industry Canada, 2001). This standard will be met by the proposed Bipole III transmission line within the ROW and beyond in fair weather; the levels will be even lower in foul weather.

Visible light

The ejection of electrons with low energy from the conductor surface during corona increases the energy levels of surrounding gas molecules, which when released gives rise to AN and RN as described above and a faint bluish light. The light produced is so weak that it typically can only be seen at night, particularly under foul weather conditions, and even then special binoculars or other magnification may be required to detect the light.

Interference with electronic devices

Global Positioning System receivers

GPS is a space-based navigation system that relies on 24 orbiting satellites circling the Earth to establish the position of a GPS receiver on the Earth. The receiver uses the radiofrequency (RF) signals sent from three or more of these satellites to determine its exact location. Naturally-occurring sources of RF (e.g., geomagnetic storms) and man-made sources of RF (e.g., TV station transmitters) are sometimes reported to interfere with GPS signals because these sources can produce interference in the same frequency ranges as used by GPS. Since GPS signals are of far higher frequency than the RN of a DC transmission line, it is very unlikely that a DC transmission line will interfere with GPS functioning.

Modern GPS receivers can receive corrections from a number of satellite-based systems with frequencies above 1 gigahertz (GHz) to improve the accuracy of positional location; this is called differential GPS (DGPS). Some GPS systems also make use of real-time kinematic (RTK) systems to improve the accuracy of the GPS system by making use of the ultra high frequency (UHF) range. Since the frequency bands of these systems are far higher than RN frequencies of concern produced by a DC transmission line, signal interference is unlikely to occur. Since the GPS signal at ground level is very weak, it is possible that some receiver designs may be susceptible to minor interference due to certain factors. Conceptually, a DC transmission line might affect GPS performance in two additional ways: (1) RN interference to Nationwide Differential GPS (NDGPS) positional corrections and (2) signal blocking and reflection. These concepts are described further below.

Nationwide differential GPS positional correction

NDGPS is a GPS system commonly used in the United States and along the southern border of Canada that was developed to improve GPS accuracy when GPS first became available. This system works together with a GPS system making use of land-based towers to transmit correction signals to GPS receivers. NDGPS uses lower frequencies to send correction signals. These lower frequency signals can overlap with the RN frequencies discharged from a DC transmission line. The likelihood of interference in each situation will depend on the GPS receiver's distance to the transmission line, as well as its distance to the closest NDGPS antenna. A momentary loss of NDGPS signal, however, should not substantially affect the accuracy of the overall positioning system. The accuracy of GPS signals is much greater today and therefore the NDGPS positional correction does not substantially improve the accuracy of current GPS receivers, which have an accuracy of a few metres. Canada terminated support for NDGPS on April 1, 2011 and alternatives to Canada-Wide DGPS Service provide corrections signals for land receivers by mobile satellite (MSAT) or UHF cellular radio (CDGPS, 2011), which are not or minimally susceptible to RN interference from transmission lines.

Signal blocking and reflection

RF signals can be blocked by physical objects (e.g., mountains) or degraded by reflections off large solid objects. The towers of a DC line, while relatively large compared to the size of a person, for example, do not have a large footprint and they are not solid. So while the towers can result in some reflections and blocking of RF signals their impact is generally momentary and insignificant. Transmission line conductors are also too thin to block or cause large reflections of RF signals. GPS and related receivers are typically configured to reduce the effects of blocked and reflected signals, resulting in a very small and temporary blockage area if it occurs. Further, the concept of multiple satellite options implies that having the signal from one of a group of satellites blocked is not consequential since the reception from the other satellites is still available.

GPS use in agriculture

As described, RN from a DC transmission line would not be expected to directly affect GPS signal reception or the reception of satellite-based positional correction signals used in equipment for farming operations. Since RTK correction signals are transmitted from antennas that are typically only a few metres high, DC transmission line towers are not expected to produce much blocking of line-of-sight signals from these sources either. Repositioning of the RTK base station antenna should resolve any issues if they occur. Signal degradation can occur due to reflections from a nearby flat-topped building or other reflecting surfaces (such as lakes). The overall performance of a GPS guidance system in agriculture depends upon a high-quality receiver, proper mounting, and good positional correction from an independent source.

Tests for DC transmission line interference to GPS

Manitoba Hydro has been questioned as to whether the presence of Bipole III will interfere with GPS systems. The RN from DC transmission lines is low intensity and occurs at frequencies that are far lower than those used by GPS systems. Because of this, the DC transmission line will not interfere with GPS signals. Manitoba Hydro requested field testing in order to confirm this conclusion. Two surveys by independent surveyors were performed using various types of GPS technologies directly beneath the two existing Bipole I and II DC transmission lines located in Manitoba's Interlake region (Pollock & Wright, 2010; Plan Group, 2011). The tests showed no interference whatsoever with any type of GPS or Global Navigation Satellite System (GNSS) technology tested, including RTK and other correction systems. The GPS receivers tested continued to operate without interruption at cm accuracies regardless of the presence of the DC transmission lines. In theory, the presence of the transmission towers themselves might occasionally attenuate satellite signals related to GPS systems (as do trees) but this was not observed during testing. A GPS receiver makes use of multiple satellites in determining its position and so the loss of one or even two of these signals will not normally result in a loss of function of the GPS systems. A limited series of measurements under a nearby 230-kV AC transmission line also did not affect the performance of the GPS receivers (Pollack & Wright, 2010).

Mining surveying equipment

Whether the electromagnetic fields from the proposed Bipole III transmission line will interfere with mining exploration survey methods depends on the distance to the line, the type of measurement equipment used for the explorations, and post-processing corrections of the acquired data. The primary methods of acquiring data involve:

1. Mapping the geomagnetic field and anomalies associated with ore deposits with very sensitive magnetometers (claimed sensitivity is 0.01 nanotesla [nT]; practical sensitivity is 0.1 nT) by ground or aerial surveys.

2. Applying time-domain AC or pulsed magnetic fields to the ground and then measuring the signal *dB/dt* during or after the collapse of the impressed magnetic field, or both. Improved resolution is achieved by placing receiver probes down in boreholes closer to conducting ore

deposits. These methods might also include measurements of weak electromagnetic fields induced in the Earth by the ionosphere or from thunderstorm activity.

3. Injecting currents into the ground through electrodes and measuring the pattern of conductivity around the electrodes.

Aeromagnetic surveying relies on an accurate measurement of the DC magnetic field from the ground to enable correction for the effects of the DC magnetic field from the transmission line. Measurement sensitivity is typically 0.1 nT after correction of time-dependent fluctuations of the magnetic field such as diurnal fluctuations (50 nT to 100 nT) and micropulsations (0.001 nT to 10 nT). Natural, magnetically-induced currents that produce magnetic fields can vary by as much as 10 nT/second, which will also affect the measurements (Pirjola, 2000). Rough estimates suggest that Bipole III might affect the DC magnetic fields to a level at or above 0.1 nT out to distances of up to about 8 to 10 km on either side of the line.[7]

Electromagnetic surveys, such as a Helicopter Electromagnetic (HEM) survey, do not rely on the Earth's natural magnetic field, but rather rely on the time and frequency response of the ground to the magnetic pulses generated by the airborne coil. Such HEM surveys have been utilized before in nickel-copper sulphide deposit exploration (Balch, undated). These measurements would not be affected by the DC magnetic field from Bipole III, but may be affected by the AC electric fields or magnetic fields associated with harmonic AC currents injected into the line by the converters at the ends of the line. Harmonic filters normally are installed at the ends of the DC transmission line to reduce the magnitude of the injected currents. Typical performance specifications for such filters are to limit the induced voltages to between 10 and 20 millivolts (mV) as measured in a 1 km test line placed in parallel with the line at a distance of 1 km from the line. The specified value typically is defined with a C-weighted average used for the evaluation of telephone interference.

Electronic medical devices

Pacemakers

The magnetic field from a DC transmission line is too weak to affect cardiac pacemakers. Since the background level of the static magnetic field in Manitoba is approximately 580 mG and the

[7] Under rare emergency operating conditions, this effect could be extended.

maximum increase from Bipole III is estimated to be about 50% above this background, the exposures to a person with an implanted pacemaker even under the transmission line will be far below the recommended limit of 0.5 mT (5,000 mG) (ACGIH, 2009).

Similarly, the static electric field from a DC line would not be expected to be a source of interference to a pacemaker. In theory, a pacemaker might be affected by an electrostatic discharge directly to the chest from a large well-insulated, ungrounded vehicle, e.g., a tractor-trailer, under a DC transmission line. The short duration of such a discharge, however, and the insulation from the ground necessary to accumulate such a charge makes it unlikely to affect a pacemaker (Stuchly and Kavet, 2005). Such an exposure might occur in some occupational environments but the magnitude, distribution, and conditions for the electric field under the Bipole III DC transmission line makes this exposure scenario less likely than exposure from the static electric field commonly associated with certain clothing in the winter.

Cochlear implants

For some persons with severe hearing loss, a cochlear implant can provide partial hearing. The device consists of a small microphone behind the ear that provides complex processing of the sound into digital electrical signals that are then transmitted over an array of wire electrodes surgically implanted in the cochlea, the auditory portion of the inner ear. The signals bypass non-functional hair cell receptors to directly stimulate the auditory nerve which is perceived as sound.

A question was raised as to whether the electric field and space charge from the proposed Bipole III transmission line would cause an electrostatic discharge sufficient to interfere with the device. To address this question, it was assumed that the cochlear implant has been tested for electromagnetic immunity as set forth in the IEC 60601-1-2 medical electrical equipment standard (IEC, 2001). As recommended in IEC 60601-1-2, immunity testing of cochlear devices to electrostatic discharge (ESD) should be tested to IEC 61000-4-2 levels that specify immunity levels of 6 kV to a contact discharge exposure and 8 kV to an air discharge exposure (EMC, 2000; Chute and Nevins, 2002; Tognola et al., 2007). Some manufacturers also test at higher immunity levels (Tognola et al., 2007).

Assuming the presence of a 150 nA/m^2 ion flux density, which is higher than expected under the Bipole III transmission line under emergency loading condition, and based on published values of the DC resistance to the ground of persons wearing shoes, standing under the Bipole III transmission line will not develop human-body potentials that would exceed the IEC immunity-test levels for a cochlear implant. The method of this analysis can be explained with reference to Figure 6.

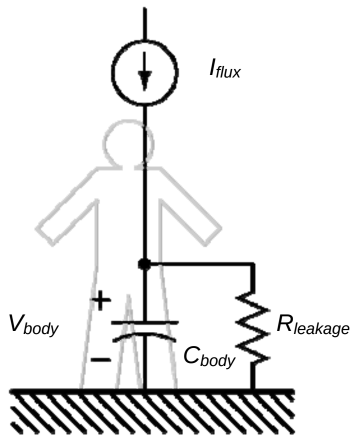

Figure 7. Charging model for person standing under the Bipole III line

I_{flux} represents the ion current collected by a person standing beneath the conductors of the Bipole III transmission line. I_{flux} develops an electric potential on surface of the body (V_{body}) by charging the body's capacitance (C_{body}). Charge collected on the body surface returns to the ground through the leakage resistance $R_{leakage}$, which models the DC impedance of footwear in contact with the Earth.

In steady state, the charging current (ion flux) and discharging current (leakage) are equal, and the potential of the human body does not change. This steady-state potential is the maximum sustained voltage that can be developed on the body the under the transmission line. A person wearing dry, new boots and standing on dry ground will have a higher leakage resistance, lower discharging current, and a higher steady-state body potential. Conversely, a person wearing wet, soiled boots and standing on damp grass will have a lower leakage resistance, higher discharging current, and a lower steady-state body potential.

A conservative estimate of the ion flux density under the Bipole III transmission line is 150 nA/m^2, i.e., for each square metre of collection area, space charge from the overhead transmission line collects at a rate of 1.5×10^{-7} coulombs per second.[8]

The collection area of a person 6 feet in height is calculated to be 5.6 m^2 based on published AC induction expressions for the human body. In particular, the short-circuit induced current I_{sc} for a person is reported by the Electric Power Research Institute (EPRI, 2006) as

$$I_{sc} = 5.4 \times 10^{-9} h^2 E \qquad (1)$$

where *h* is height in m, and *E* is the unperturbed electric field in units of V/m. Expression (1) is a specific form of the more general expression

$$I_{sc} = j\omega\epsilon ES = \frac{ES}{3 \times 10^8} \qquad (2)$$

where $j\omega$ is the angular frequency in radians per second (377 rad/s), ε is the permittivity of free space (8.85×10^{-12} F/m), and *S* is the collection area of a charging object in units of m^2. Solving (1) and (2) for *S*, the collection area of a person increases with height according to the expression

$$S = \frac{5.4 \times 10^{-9} h^2}{\omega\epsilon} = 1.619 \cdot h^2 \qquad (3)$$

where *h* is height in m, *S* = 5.6 m^2 for a person 1.85 m (6 feet) tall. The total current I_{flux} is the product of the charge collection area and ion flux density. Based on the parameters above, I_{flux} = 833 nA, less than one-millionth of one A.

$R_{leakage}$ is estimated by the DC resistance of persons in shoes, as reported by Reilly (Reilly 1998a, 1998b). Figure 7, reproduced from these sources, is explained by the author as follows:

> Footwear can add significantly to the total path resistance, as illustrated in [Figure 7]. This figure plots the distribution of DC resistance on individuals standing on various surfaces, with a current pathway from a large electrode held in the hand, to a nearby driven ground rod in the soil. The measurement voltage was 500 V. In all cases, footwear was dry, except for surface moisture on which the person stood. In general, leather soles are much more conductive than rubber soles. If leather soles become wet, their resistance can fall greatly. Grass blades that touch the sides of the shoes can also significantly lower their resistance. The curves labeled "damp grass" apply to individuals standing on short grass; in the "wet

[8] For air ion concentrations of 130 thousand ions/cm^3 calculated for the Bipole III transmission line, 150 nA/m^2 charging current corresponds to a 7.2 m/s ion drift velocity in the DC electric field beneath the DC conductors.

grass" condition, subjects first stood briefly on 1cm of water before stepping on the grass. In tall grass (e.g., 8cm), we would except to see much larger percentages of low resistances.

Figure 7 shows that all measurements of DC leakage resistance were less than 2 giga-ohms (GΩ). Hence, 2 GΩ was used as a conservative upper bound on $R_{leakage}$.

Using the parameters described above, the potential rise V_{body} of a person standing beneath the transmission-line conductors is $R_{leakage} \cdot I_{flux}$ = 1.6 kV, a value 3.75 times lower than the IEC immunity test level of 6 kV. It should be noted that this result is conservative in at least two respects:

1. parameters in the charging model (Figure 6) are a conservative estimate of actual parameters; and

2. the 6 kV immunity test level is applied directly to the medical device, whereas contact currents and charging in the human body do not—in many circumstances—electrically stress an implanted device directly.

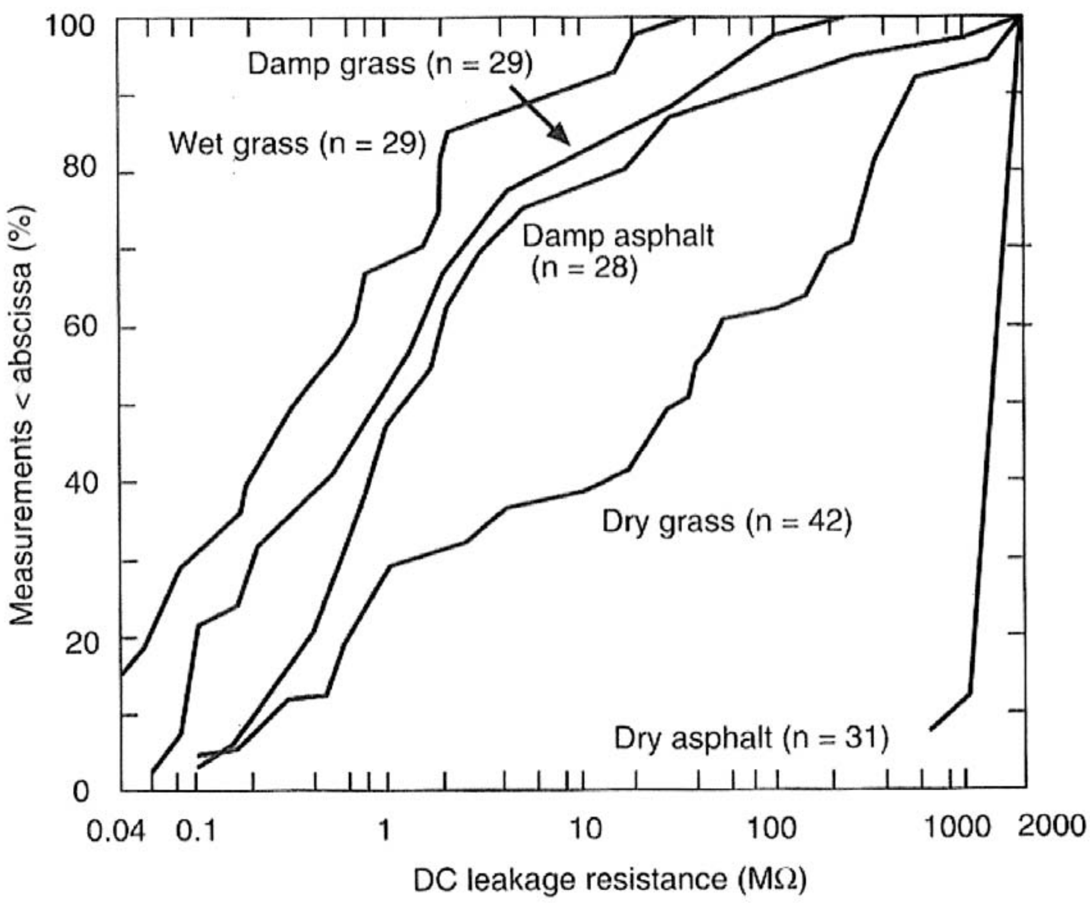

Figure 8. DC resistance of persons through shoes, standing on various surfaces (reproduced from Reilly 1998a, 1998b)

Dairy Cattle, Wild Animals, and Plants

Dairy cattle and DC transmission lines

Two studies have been conducted to respond to the concerns of farmers about possible effects of the electrical environment of DC transmission lines on dairy cattle. The first study was conducted by investigators at the University of Minnesota who used the records of the Dairy Herd Improvement Association to study the health and productivity of approximately 500 dairy herds (about 24,000 cows) from farms located near the ±400-kV CPA/UPA DC transmission line in Minnesota (Martin et al., 1983). Veterinary records for a 6-year period were examined, from 3years before to 3 years after energization of the line in 1979. The herds were grouped according to distance of the farmstead from the transmission line, with the closest herds less than 0.25 miles (400 m) from the line, and the farthest between 6 and 10 miles (~10 to 16 km).

Endpoints selected for study included milk production per cow, herd average of milk production, milk fat content, and measures of reproductive efficiency, among others. The health and productivity of the herds was found to be the same before and after energization and also was found to be unrelated to distance of the herds from the transmission line.

In another study, investigators at Oregon State University compared the health and productivity of 200 cow-calf pairs randomly assigned to pens directly under or 615 m away from the Pacific Intertie ±500-kV DC transmission line. No differences between the animals in the exposed and control pens were noted with regard to breeding activity, conception rate, calving, calving interval, body mass of calves at birth, body mass at weaning, or mortality over a 3-year period. The average exposure of the animals in pens under the line was about 5 kV/m and 13,000 ions/cm^3 (Angell et al., 1990). As part of this study, the investigators also monitored the activities of the exposed and control cattle at 15-minute intervals during a 24-hour period each month (Ganskopp et al., 1991). The distribution of cattle along feed troughs in the exposed and control pens was similar and unrelated to measures of the static electric field and there were no major differences in the time spent in various behaviors. Although small differences in the distribution of cattle within the pens were noted, the investigators reported that the differences were not correlated with fluctuations in the static electric field or AN levels.

Plants

The studies performed on plants exposed to DC magnetic fields have predominantly focused on effects on genetic, growth, and enzymatic activities. No adverse genetic effects were reported (McCann et al., 1993) and the results of studies on growth were inconsistent (Simon, 1989).

A substantial amount of laboratory research has been performed on the effect of air ion exposure on plants. This research, like that associated with air ion research on animals and humans, consists of a few responses that have not been replicated and that are of questionable quality.

Most of the work studying the effect of air ions on several types of plants, including oat and barley, was performed under the direction of Krueger and co-workers. They reported a significant increase in the plants' dry weight (Krueger, et al., 1962, 1963) when exposed to concentrations ranging from 5,000 ions/cm^3 to 13,000 ions/cm^3. Other investigators found that plants grown in ionized air showed enhanced fresh weights along with enhanced growth, but no change in dry weights (Wachter and Widmer, 1976). An explanation for this observation is that the increase in growth was at the expense of the existing plant mass. Similar reports of enhanced growth, fruit yield, and quality are reported for tomato plants exposed to air ions at levels in the range of 10,000 ions/cm^3 (Yamaguchi and Krueger, 1983).

When seedlings of barley are cultivated in an iron-deficient nutrient medium, they eventually develop an iron deficiency. Krueger et al. (1963, 1964) reported that iron deficient seedlings cultivated in an atmosphere of air ions, either (+) or (-) polarity, biochemical indicators associated with iron deficiency were increased. This may merely reflect, however, the greater demand for iron in a more rapidly growing seedling that had been exposed to air ions, which was also reported (Krueger et al., 1963).

Several studies have examined the effect of DC transmission lines on plants and are more relevant to real world circumstances than observations made in a laboratory setting. An outdoor test facility in Japan was designed to examine the possible effects of a DC power line on the growth of wheat plants positioned at 3 m, 4.5 m, and 6 m below the conductors under the +100kV and -100-kV conductors (Endo et al., 1979). The electric field intensities were calculated to be 42 kV/m, 65 kV/m, and 84 kV/m, respectively at the above designated line heights. The investigators concluded that there were "no significant differences" between the control and exposed plants with regard to development and differentiation, but in the last month of the growing season the heights of plants under the conductors were 5% lower than control plants and 12-26% fewer tillers were measured on exposed plants. Differences among plants in the exposed group, however, were not clearly related to differences in the strength of the applied electric field. Even with these observed differences between exposed and control plants, the harvest yield or composition of the stems or seeds was not reported to be affected. Crops on the ground under the proposed Bipole III transmission line would be 13 m below the conductors, not 3-6 m as in this study, and the maximum electric field will be significantly lower than in the Endo et al. (1979) study.

Krupa and Pratt (1982) surveyed the growth, condition, and disease incidence in crops grown in 25 plots located 30.5 m from the centerline of a ±400-kV DC transmission line. No effects attributable to the presence of the line (including exposures to O_3 or to electric or magnetic fields) were detected based upon reference data of the local Animal and Plant Health Information System.

The above research on plants provides some indication that plants in laboratory conditions may exhibit enhanced growth in response to varying levels of air ions, but further research is needed to confirm such observations and to determine the potential mechanism. The evidence for responses of plants to other aspects of the DC transmission environment, i.e., the electric field and magnetic field, is not sufficient to conclude these exposures have any reliable influence on plants.

Wild animals

Griffith performed a study to investigate the effect of the Pacific Intertie DC transmission line in Oregon on the plant and animal communities when operating at ±400 kV (Griffith, 1977). He performed systematic sampling of these populations with primary emphasis on crops, natural vegetation, songbirds, raptors, small mammals, pronghorn antelope (*Antilocapra americanca*), and mule deer (*Odocoileur hemionus*). There were some species that were influenced, either positively or negatively, by the presence of the transmission line. Overall, species that were negatively influenced were those that needed undisturbed plant species, or have some specialized type of behavior with which transmission line structures interfere, such as robins, Brewer's sparrows, and pinon mice. Those species that were positively affected used the transmission line structures as part of their feeding, hunting, or resting habitats, including certain types of raptors and Townsend's ground squirrels. The observed impacts were believed to be related to the physical presence and construction of the line rather than the electrical environment associated with the line. It is not possible, however, to conclude from this study alone that all observed differences were the result of the physical change to habitat by construction of the line.

The Earth's geomagnetic field has been shown to be detected by a variety of organisms ranging from bacteria to homing pigeons (Kirschvink, 1982). A change in the intensity or orientation of the Earth's geomagnetic field has been reported to affect orientation or navigational clues that are used by some animals.

Blakemore demonstrated that certain anaerobic bacteria swim to the North Pole in the northern hemisphere, the South Pole in the southern hemisphere, and in both directions at the equator (Blakemore, 1975; Blakemore et al., 1982). Higher organisms also demonstrate sensitivity to the Earth's geomagnetic field. For example, homing pigeons have a magnetic compass sense and honeybees perform a waggle dance oriented to the Earth's geomagnetic field. The mechanism allowing for this magnetic sensitivity appears to be a receptor for magnetic fields—chains of iron oxide (Fe_3O_4), known as magnetite. The presence of Fe_3O_4 has been described for a number of species including birds, bees, bacteria, and recently, humans. To date, Kirschvink and associates are the only investigators that have observed Fe_3O_4 in humans (Kirschvink et al., 1992) and there is no confirmed behavioral or physiological evidence that humans can detect static magnetic fields.

While there is evidence that DC magnetic fields can be detected by some avian species and bats (Holland et al., 2006) and used as a navigational aid, the research does not suggest that the behavior of birds or other species would be adversely affected by the relatively small change in the magnetic field on or above the ROW of the proposed Bipole III transmission line.

Most wildlife is shielded from electric fields of transmission lines by surrounding vegetation. Thus, small ground dwelling species such as mice, salamanders, and snakes are usually not exposed to electric fields from DC transmission lines. In addition, organisms which live underground, such as moles and woodchucks, are completely shielded from electric fields by the soil. Hence, only large wildlife species, such as deer, elk, and moose, have potentially greater exposure to electric fields, since they can stand taller than the surrounding vegetation. The duration of potential exposure for deer and other large mammals, however, is likely to be limited to foraging bouts or the time it takes to cross under the line. Since electric fields do not enter the body, interactions with wild animals would be limited to the perception of fields and charges on the surface of the body, similar to domesticated large animals (cattle) for which no effects on feeding and growth have been reported. An analysis of the orientation of deer and cattle in satellite photos has suggested that they tend to orient their bodies along the north-south field lines of the geomagnetic field (Begall et al, 2008). Other investigators have been unable to confirm this finding (Hert et al., 2011a) but Begall et al. (2011) dispute these data and analyses, to which Hert et al. (2011b) have replied.

In conclusion, an evaluation of studies of human and animal exposures to magnetic fields, electric fields, and space charge conducted in laboratories and around DC transmission lines does not show that the electrical environment of a DC transmission line would have an adverse impact on these populations or on plants.

Ancillary DC Facilities

Converter Station

Converter stations will be connected to each end of the Bipole III line to transfer AC to DC power at the northern converter and DC to AC power at the southern converter. In addition there will be associated equipment and facilities to connect to AC transmission lines and switching facilities.

The electric and magnetic fields associated with equipment in the converter station would not be expected to cause field levels outside the boundaries of the large proposed sites to be significantly elevated except where power lines, e.g., Bipole III, or connections to the AC grid traverse the boundary.

The converters can be a potential source of AC harmonics, switching transients, and RN. These emissions can be reduced by filtering the converter output. Assuming standard design practices to minimize RF interference from the converter station and electrode line, harmonics and RF are not likely to be a problem, and if interference is detected, it will be mitigated.

Ground electrode/feeder line

Bipolar operation

The DC line will be grounded at the converter station through a twin conductor line (similar in appearance to a standard distribution line seen along many Manitoba roadways) to a remote buried ground electrode. The purpose of the ground electrode is to correct minor imbalances in the current flows between the (+) and (-) conductors and so the DC electric and magnetic fields on the electrode site and under the feeder line will be very low. This operating mode is expected to occur about 92% of the time based on historical data for Bipoles I and II.

Monopolar operation

During emergency and maintenance conditions the line may operate in a monopolar mode to allow emergency operation if the valve groups supporting one pole or one of the conductor bundles is out of service. The levels of DC electric fields, air ions, and ion current density will increase slightly (~10%) on the ROW and the edge of the ROW closest to the operating pole compared to bipolar operation; levels will decrease by a larger percentage at the edge of the ROW closest to the inactive pole. In contrast, AN and RN levels will decrease across the ROW, particularly during monopolar negative pole operation.

The ground electrode is designed to operate at a continuous current of 2,000 A and a higher current of 2,200 A for up to 60 days (design option 1). Another design option evaluated by Teshmont was continuous current of 2,500 A and 60 days of operation at 2,750 A. The higher short-term loadings in design option 1 were assumed for all modeling. The magnetic field level above the ground electrode will be less than 1,000 mG at 1 m except where the feeder line enters the ground where it will be higher but still far below the ICNIRP exposure guideline level.

The static magnetic field level for a current flow on the feeder line of 2,200 A would rise to about 1,200 mG and the electric field level to less than 0.8 kV/m. The step potentials during monopolar operation have been projected to be 5-9 V/m (Teshmont, 2010, 2011) and these levels would not pose a shock risk to humans or animals on site or off site. This conclusion would apply to fish in a stream 800 m outside the southern electrode site.

AC harmonic currents on the electrode line, if not fully mitigated by the design of the converter station and filters, might be a possible source of interference to telephone communication; if found to be a problem, this can be mitigated.

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Appendix 1

Modeling of the Electrical Environment for Proposed DC Components of the Bipole III Project

Exponent®

Health Sciences and Electrical and Semiconductors Practices

Modeling of the Electrical Environment for Proposed DC Components of the Bipole III Project

Modeling of the Electrical Environment for proposed DC Components of the Bipole III Project

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August 2, 2011

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Acronyms and Abbreviations

μPa	Micropascal
μVm	microvolt/metre
A	Ampere
AC	Alternating current
AM	Amplitude modulated
A/m^2	Amperes per square metre
AN	Audible noise
CISPR	Comité Internationale Spécial des Perturbations Radioelectrotechnique
dB	Decibel
dB-A	Decibel on the A-weighted scale
dBμV/m	Decibel above 1 microvolt per metre
DC	Direct current
EPRI	Electric Power Research Institute
FM	Frequency modulated
G	Gauss
GPR	Ground potential rise
Hz	Hertz
kA	Kiloampere
kHz	Kilohertz
km	Kilometre
ICNIRP	International Commission on Non-Ionizing Radiation Protection
$ions/cm^3$	Ions per cubic centimetre
kV	Kilovolts
kV/m	Kilovolt per metre
m	Metre
mG	Milligauss
MHz	Megahertz
mm	Millimetre
mT	Millitesla
MW	Megawatt

NRPB	National Radiological Protection Board
OPGW	Optical protection ground wire
RF	Radiofrequency
RN	Radio noise
ROW	Right-of-way
rms	Root mean square
SPL	Sound pressure level
V/m	Volts per metre

Notice

At the request of Manitoba Hydro, Exponent conducted specific modeling and evaluations of components of the electrical environment of the Bipole III project. This report summarizes work performed to date and presents the findings resulting from that work. In the analysis, we have relied on geometry, material data, usage conditions, specifications, regulatory status, and various other types of information provided by the client. We cannot verify the correctness of this input data, and rely on the client for the data's accuracy. Although Exponent has exercised usual and customary care in the conduct of this analysis, the responsibility for the design and operation of the project remains fully with the client.

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 investigation 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 herein 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.

Introduction

Manitoba Hydro has proposed to improve reliability of the province's electricity supply by constructing a new ±500 kilovolt (kV), 2,000 megawatt (MW) overhead direct current (DC) transmission line known as Bipole III. The 1,384 kilometre (km) transmission line will connect a new converter station in northern Manitoba northeast of Gillam (Keewatinoow) to a new converter station east of Winnipeg at the Riel Station site.

This report summarizes calculations of the DC electrical environment around the DC portion of the proposed Bipole III transmission line.[1] Section 1 provides a brief summary of the proposed DC transmission line designs. Section 2 discusses the methods used for modeling the DC electric and magnetic fields, corona phenomena including audible noise (AN) and radio noise (RN), air ion density, and ion current density. The modeling results for Bipole III are presented in Section 3 and compared to the electrical environment of Bipole I/II in Section 4. An evaluation of the electric and magnetic fields associated with the ground electrodes and connections to the proposed Keewatinoow and Riel converter stations is provided in Section 5 and Section 6 discusses the converter station. Finally, assessment criteria and conclusions are discussed in Section 7.

1 The calculations of the electrical environment around the portion of the proposed Bipole III transmission line project related to Northern Collector lines that will transmit electricity as alternating current (AC) are summarized in a separate report, "Modeling of the Electrical Environment for Proposed AC Components of the Bipole III Project."

1. Bipole III DC Transmission Line Designs

Figure 1 and Figure 2 are schematic diagrams of the structure designs considered for Bipole III. The Bipole III transmission line will be strung on steel tower structures on a 66 metre (m) wide right-of-way (ROW), with an average tower spacing of approximately 480 m resulting in two to three towers per km. In the southern half of the route, the line will be constructed on self-supporting towers (Figure 1). In the northern part of the route, guyed towers (Figure 2) will be used in forested areas and other areas that are compatible with the use of this tower type. The primary difference between these two tower structures is in the separation between the conductor bundles and the diameter of the optical protection ground wire (OPGW) that is used. The two conductor bundles (each consisting of three subconductors) will be strung under self-supporting lattice towers (Figure 1) with a separation between the conductor bundles of 15.5 m; the tower uses a 17.5 millimetre (mm) diameter OPGW. The guyed tower (Figure 2) has a conductor bundle separation of 15.0 m and uses a 13.4 mm diameter OPGW (Appendix A).

The existing Bipole I and Bipole II transmission lines are supported on guyed towers as shown in Figure 3.

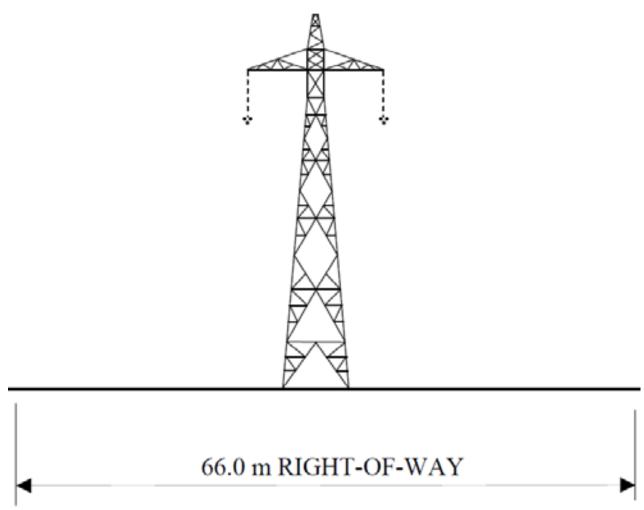

Figure 1. Bipole III – self-supporting suspension lattice steel tower

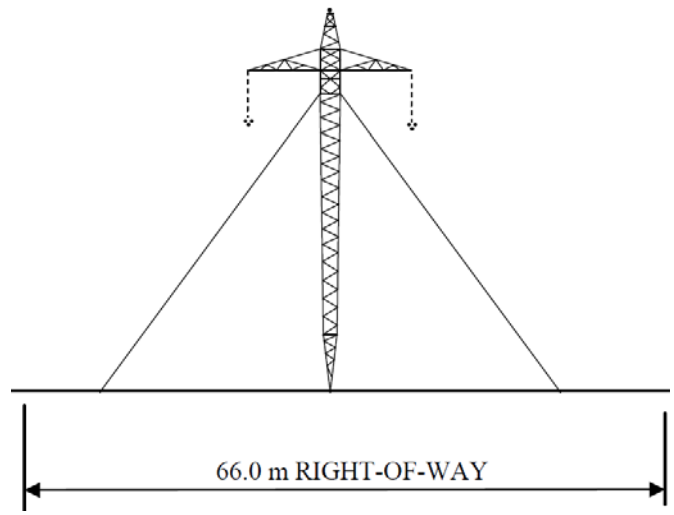

Figure 2. Bipole III – guyed suspension lattice steel tower

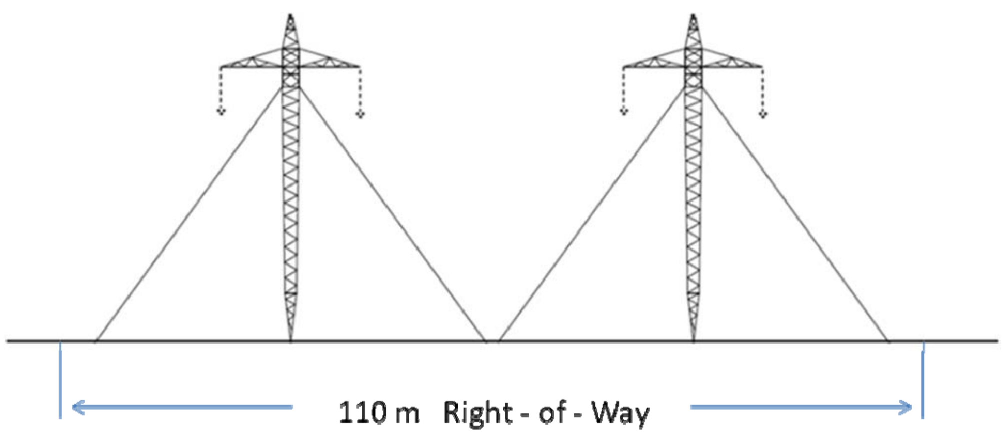

Figure 3. Bipole I and II – guyed suspension lattice steel tower

2. Methods

DC electric and magnetic field and ion calculations

The design parameters and operating conditions used in the modeling of the electrical environment around the Bipole III DC transmission line and the Bipole I and II DC transmission lines are summarized in Appendix A.

Levels of DC electric fields, DC magnetic fields, small air ions,[2] AN, and RN were modeled using the methods developed by the Electric Power Research Institute (EPRI) at the High Voltage Transmission Research Center and incorporated in the EPRI TL Workstation. This method is based on a saturated corona condition. The degree of corona saturation is dependent on the conductor contamination condition (roughness) and is dependent on weather, season, and conductor polarity.

Electric and magnetic fields are expressed as the resultant (root mean square [rms]) of magnetic field components measured in the x-, y-, and z-axes.[3] The field and ion levels as well as AN and RN were calculated along a profile perpendicular to the lines at midspan at a standard reference height of 1 m above ground in accordance with the standard method for measuring fields near power lines (IEEE Standard 1308-1994). The midspan location has the lowest line clearance to ground and results in the highest field and ion density levels along the profile. DC electric field and ion density levels can vary depending on wind, conductor contamination, and weather. Expected median (L_{50}) electric field and ion levels for the DC lines were calculated for fair weather, no-wind, warm, wet summer conditions with infrequent polarity reversals. Electric fields, ion density, and magnetic fields will vary with the height of the conductors above ground and so calculations of these parameters were also made for a contingency line load = 2,500 MW

[2] A small air ion is "an ion comprised of molecules or molecular clusters bound together by charge. Mobilities are in the range of $10^{-5}m^2/V\cdot s$ to $2 \times 10^{-4}m^2/V\cdot s$. Typical radius is less than $1 \times 10^{-9}m$" (IEEE Std. 1227, 1990).

[3] Root-mean-square refers to a common method of reporting the effective magnitude of voltage, current, or electromagnetic fields of a transmission line. The x, y, and z-axes refer to the vertical, transverse, and longitudinal directions relative to the transmission centerline. The magnetic field calculations assume a uniform ROW cross-section with no longitudinal component of the magnetic field, an assumption confirmed by measurements and algorithms developed by the Bonneville Power Administration, a division of the U.S. Department of Energy.

and an emergency line load = 4,000 MW, where the conductors will be lower to the ground than at typical loading. The DC magnetic field from the line will vary with the line loading (current). When the loading on the lines is less, the magnetic fields will be lower. The DC magnetic field from the line will either increase or decrease the geomagnetic field from the earth depending on the orientation of the lines because the fields from these two sources add vectorially (see Figure 6). The earth's geomagnetic field in the area of Winnipeg was estimated to be 580 milligauss (mG) (NGDC, 2010).

Levels of ion current density (J) in amperes per square metre (A/m^2) were computed from the following expression:

$$J=10^5 * nekE$$

Where n is the ion density in ions per cubic centimetre ($ions/cm^3$), e is the charge per ion in Coulombs/ion ($1.6*10^{-19}$ C/ion), k is the ion mobility (positive ions: $k^+ = 1.15$ $cm^2/V\cdot s$ and negative ions: $k^- = 1.5$ $cm^2/V\cdot s$), and E is the electric field in kilovolts per metre (kV/m).

DC audible noise calculations

Audible noise (AN) results from the partial electrical breakdown of the air around the conductors of a transmission line (corona). In a small volume near the surface of the conductors, energy and heat are dissipated. Part of this energy is in the form of small local pressure changes that result in AN. This AN can be characterized as a hissing, crackling sound. The levels of AN are lower in foul weather than in fair weather when the conductors of a DC line are wet.

The amplitude of a sound wave is the incremental pressure resulting from sound above atmospheric pressure. The sound-pressure level (SPL) is the fundamental measure of AN; it is generally measured on a logarithmic scale with respect to a reference pressure. The SPL in decibels (dB) is:

$$SPL = 20 \log_{10} (P/P_0) \text{ dB}$$

where P is the effective rms sound pressure and P_0 is the reference pressure of 20 micropascals (μPa), which is considered the threshold for human hearing. The human response depends on frequency, with the most sensitive range roughly between 2,000 and 4,000 Hertz (Hz). The frequency-dependent sensitivity is reflected in various weighting scales for measuring AN. The A-weighted scale weights the various frequency components of a noise in approximately the same way that the human ear responds. In this report, AN levels are expressed in decibels on the A-weighted scale (d-BA) as median L_{50} values, which are the sound-pressure levels exceeded 50 percent of the time.

In order to account for fluctuating noise levels, statistical descriptors are used to describe AN. AN levels in this report are expressed as 50 percent exceedance values (median or L_{50} values) during fair or foul (steady rain) conditions.

An altitude of 275 m (~900 feet) and a height of a sound receiver of 1.52 m (5 feet) was assumed for the calculation of DC AN for Bipole III, and an altitude of 300 m was assumed for Bipoles I and II as these lines cross higher terrain. AN levels will increase at higher altitudes.

DC radio noise calculations

Overhead transmission lines can generate RN in the bands used for the reception of radio signals. Two potential mechanisms for interference are gap discharges and corona. Corona activity, described above as a source of AN, also induces impulsive currents along a transmission line. In turn, these induced currents cause wide-band radiofrequency (RF) noise fields that can affect radio and television reception. RN can produce interference to an amplitude-modulated (AM) signal such as a commercial AM radio audio signal (520-1720 kilohertz [kHz]) or the video portion of an analog television signal. Frequency-modulated (FM) radio stations and the audio portion of an analog television signal (which is also FM) are generally not affected by electromagnetic noise from a transmission line. The advent and use of digitally encoded radio and television signals will also make the program material less susceptible to interference effects from electromagnetic noise.

Gap discharges are an intermittent phenomenon that is more common in distribution lines and low-voltage transmission lines. Electrical discharges on these lines can occur where small gaps develop between metallic line hardware, such as insulators, clamps, or brackets. Discharge across these gaps can cause incidental interference to radiocommunication services, in which event the sources of gap-type interference can be located and repaired. Gap discharges occur less frequently on high-voltage transmission lines, and the proposed line will be constructed with hardware that eliminates gap-type interference.

RN levels in this report are expressed in dB above 1 microvolt per meter (dBμV/m) to describe the electric-field intensity incident upon a reference antenna at 500 kHz as recommended by Industry Canada (2001). Weather has a large influence on corona-generated RN, as it does for AN. As with AN, corona-generated RN also varies in time. In order to account for fluctuating noise levels, statistical descriptors are used to describe RN. RN levels in this report are expressed as 50 percent exceedance values (median or L_{50} values) during fair or foul (steady rain) conditions.

An altitude of 275 m (~900 feet) and a height of a RN receiver of 1 m (3.28 feet) were assumed for the calculation of RN for Bipole III, and an altitude of 300 m was assumed for Bipoles I and II as these lines cross higher terrain. RN, like AN, is also more pronounced at higher altitudes.

3. Modeling Results for the Bipole III DC Transmission Line

The assessment below covers normal bipolar operation of the line. For the results of modeling for monopolar operation that would result from a failure of one polarity valve group see Appendix B (Modeling results: positive pole, monopolar operation using metallic return) and Appendix C (Modeling results: negative pole, monopolar operation using metallic return). In the monopolar mode both conductors are available for use even if the valve group serving one pole is down. Switching would be done in the converter yard to bypass the unavailable valve groups in the converter terminals at both ends of the line thereby connecting the available conductor to the neutral bus in each of the affected converter stations and finally interrupting the electrode line in one of the two terminals. This will force the current into the metallic conductor so the conductors for both poles will still be used. While this has approximately the same level of loss as bipolar operation, the loss is higher than using a ground return; however, it avoids shutting down the entire DC link and, therefore, avoids operation with continuous ground currents.

Another mode is monopolar operation with only one pole (set of line conductors), using the ground for the return current. This would be the monopolar operating mode with the lowest loss; however, this mode might be limited to rare contingency conditions in which one conductor bundle on the line is unavailable. In this case, the conductive ground between the northern and southern electrodes would serve to complete the circuit. The effect on the electrical environment would be similar to that presented in Appendices B and C, but the magnetic field profiles would be asymmetric because of the loss of current on one of the overhead conductor bundles and the magnetic field values would be somewhat higher.[4] The conclusions presented in Section 7 will include effects related to both bipolar and monopolar operation.

[4] Under ground-return monopolar operation, the peak DC magnetic field would be <404 mG on the ROW and <177 mG at the edge of the ROW (Appendices B and C).

Magnetic fields

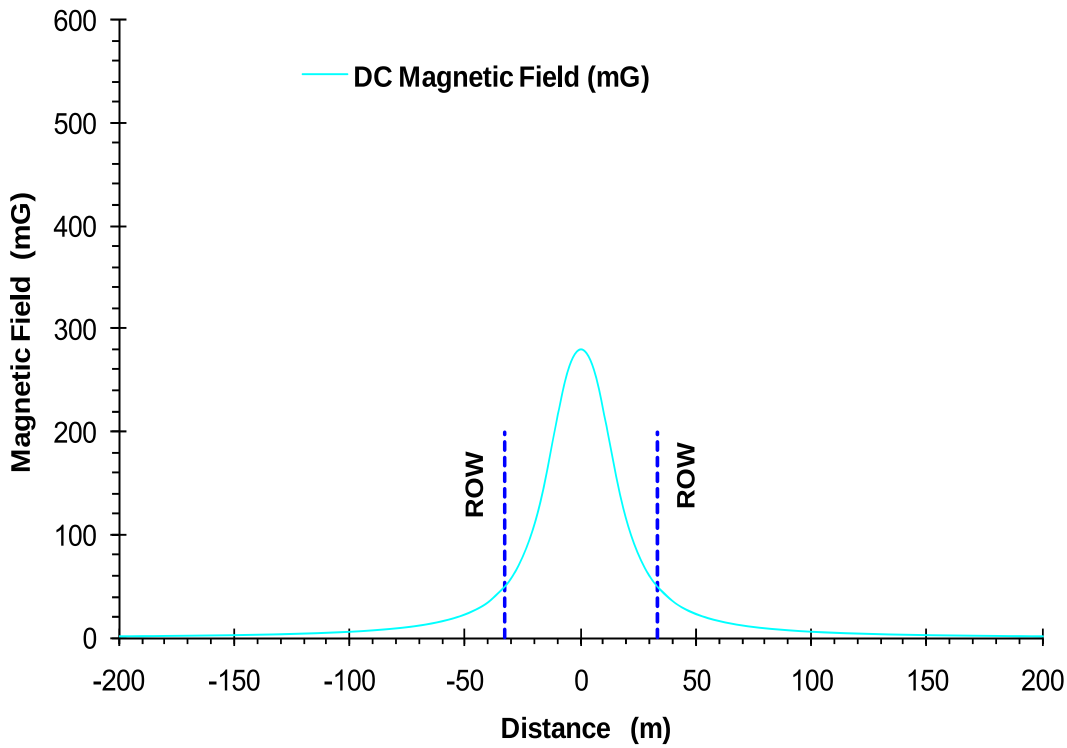

Figure 4. DC magnetic field profile for Bipole III with guyed tower, typical load (2,000 MW)

Table 1. DC magnetic field levels (mG) from Bipole III, guyed tower

Load Conditions*		ROW Edge (-33 m)	Profile Peak (within ROW)	ROW Edge (33 m)
Typical Load	Total (mG)	49.8	280.2	49.8
Contingency Load	Total (mG)	62.5	358.9	62.5
Emergency Load	Total (mG)	102.7	666.7	102.7

*Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

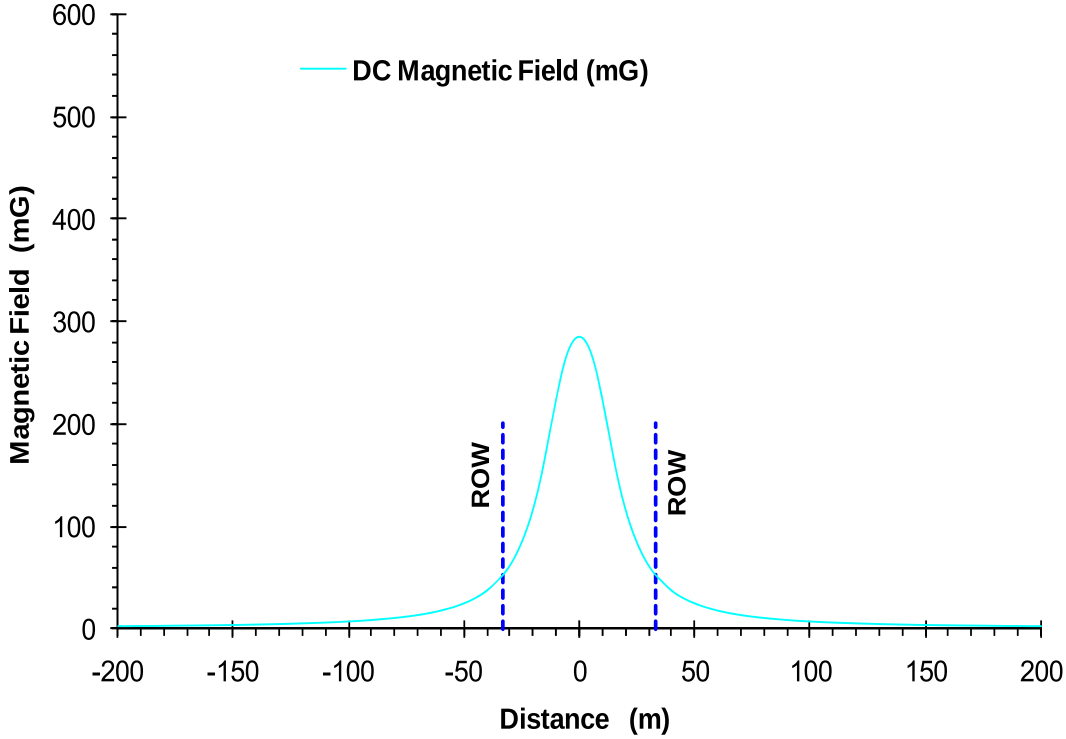

Figure 5. DC magnetic field profile for Bipole III, with self-supporting tower, typical load (2,000 MW)

Table 2. DC magnetic field levels (mG) for Bipole III, self-supporting tower

Load Conditions*		ROW Edge (-33 m)	Profile Peak (within ROW)	ROW Edge (33 m)
Typical Load	Total (mG)	51.5	284.0	51.5
Contingency Load	Total (mG)	64.7	363.6	64.7
Emergency Load	Total (mG)	106.4	673.7	106.4

*Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

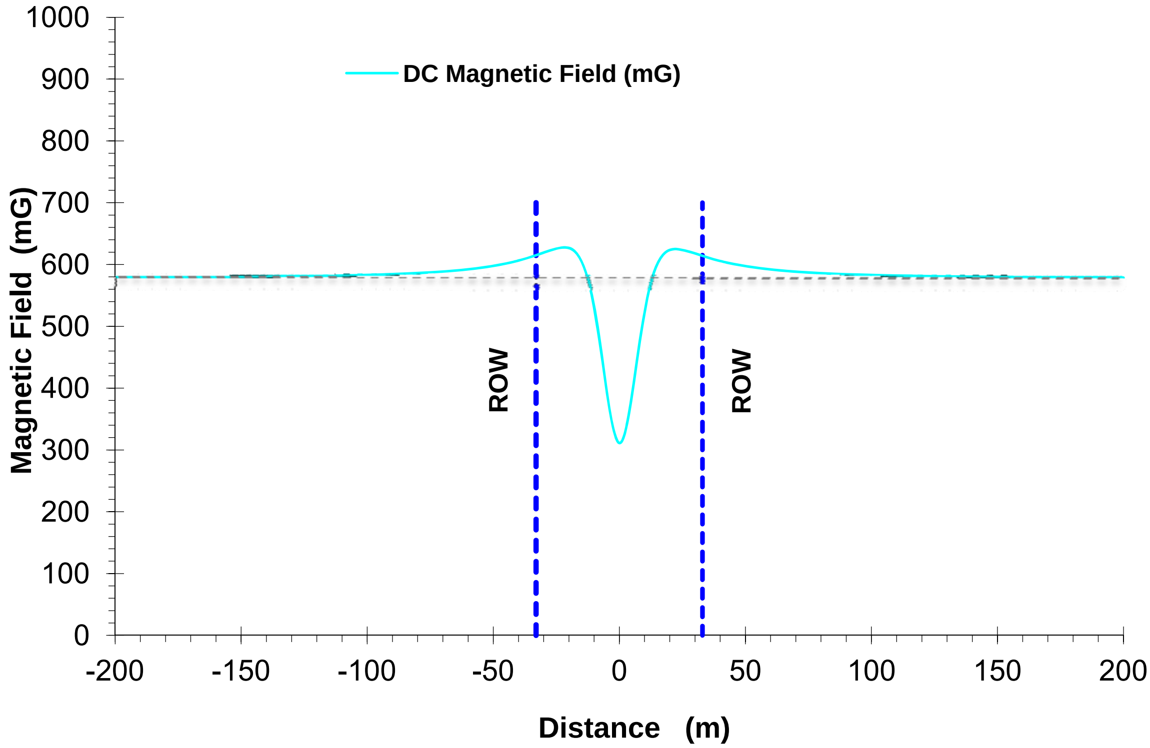

Figure 6. Example of total DC magnetic field (the earth's geomagnetic field plus the DC magnetic field) for Bipole III, with self-supporting tower

Line orientation is north-south, and the cross-section view faces north. The dashed horizontal line indicates the level of the geomagnetic field alone.

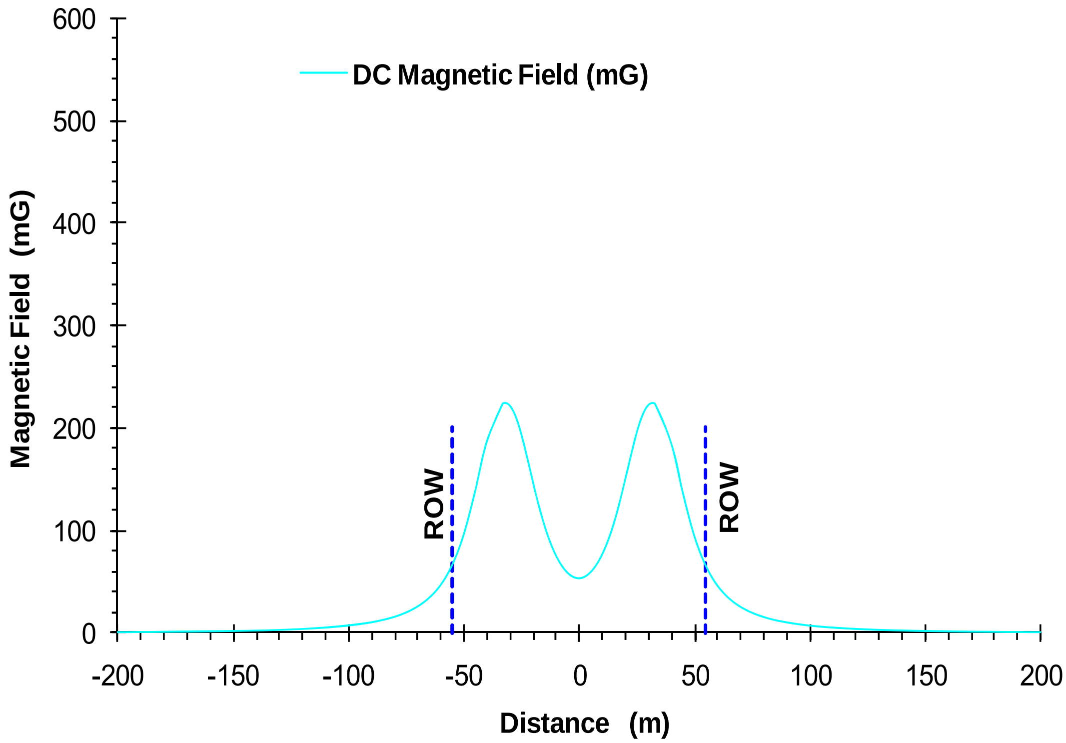

Figure 7. DC magnetic field profile for guyed tower Bipole I and Bipole II, typical loading

Table 3. DC magnetic field levels (mG) for Bipole I and Bipole II

Load Conditions*		ROW Edge (-55 m)	Profile Peak (within ROW)	ROW Edge (55 m)
Typical Load	Total (mG)	65.5	224.1	65.4

*Typical load – Bipole I = 1,559 MW; Bipole II = 1,681 MW

Electric fields

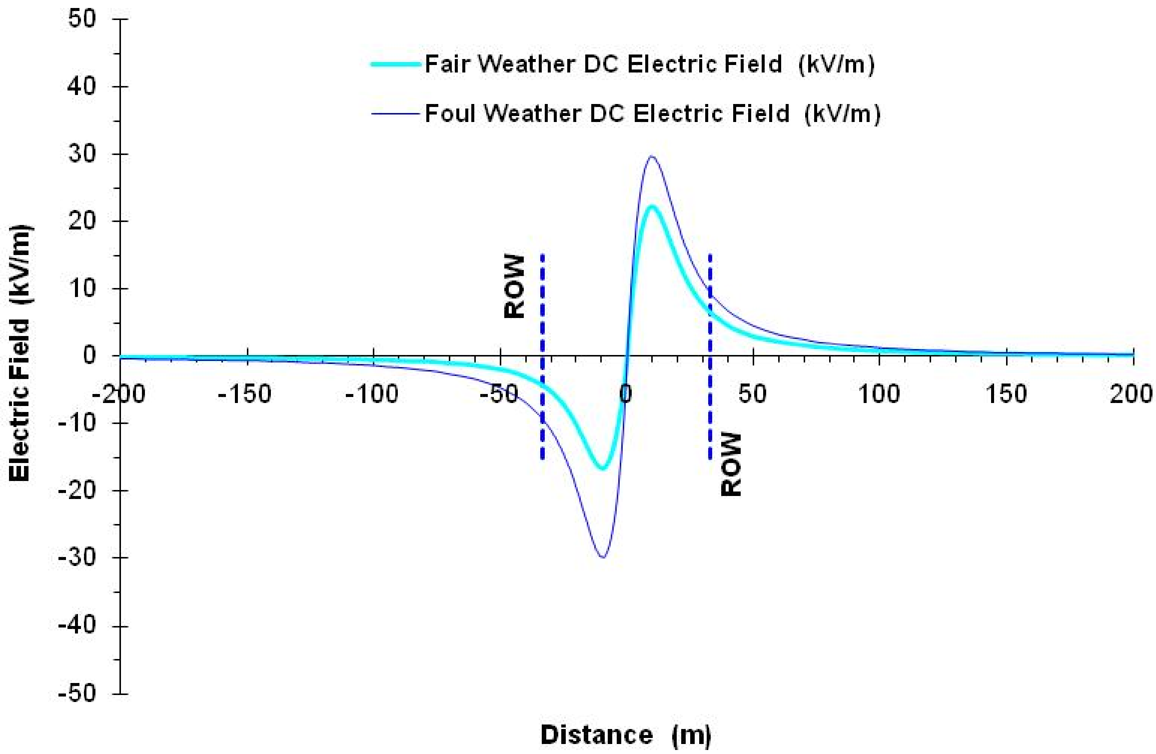

Figure 8. DC electric field profile for Bipole III, with guyed tower, typical loading (2,000 MW)

Table 4. DC electric field levels (kV/m) for Bipole III with guyed tower

Load Conditions*		ROW Edge (-33 m)	Profile Peak (within ROW)		ROW Edge (33 m)
Typical Load	Fair (kV/m)	-4.3	-16.5	22.2	6.5
	Foul (kV/m)	-9.3	-29.8	29.8	9.3
Contingency Load	Fair (kV/m)	-4.3	-16.9	22.7	6.5
	Foul (kV/m)	-9.4	-30.5	30.5	9.4
Emergency Load	Fair (kV/m)	-4.3	-19.6	26.2	6.4
	Foul (kV/m)	-9.3	-34.9	34.9	9.3

*Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

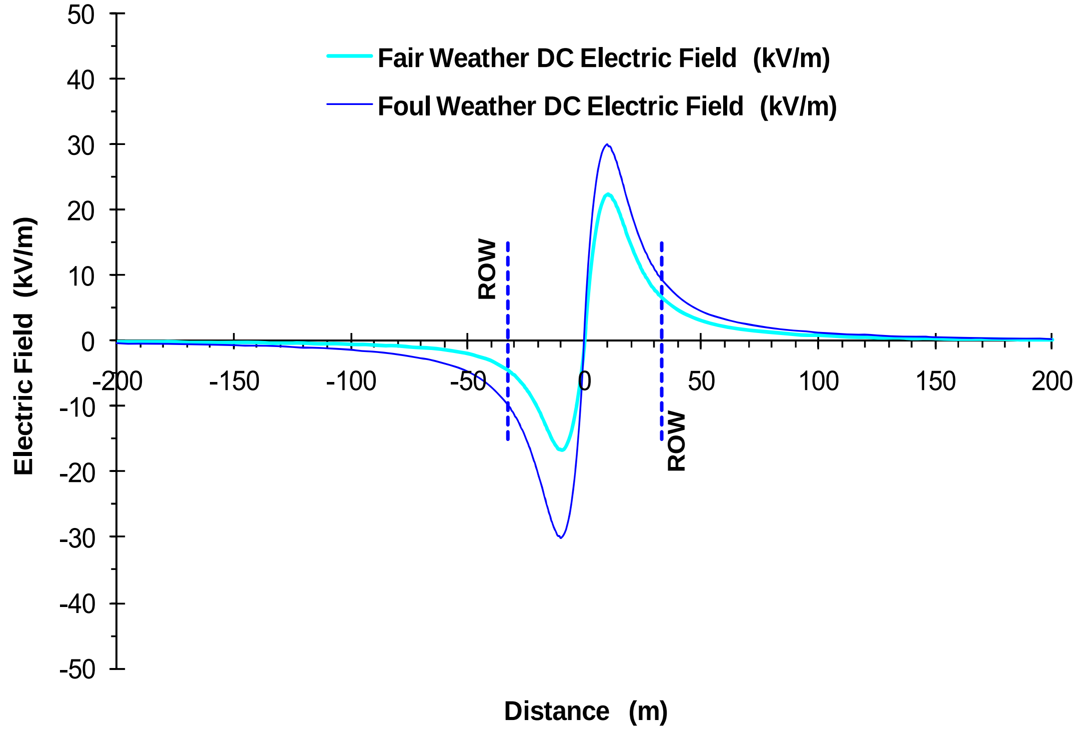

Figure 9. DC electric field profile for Bipole III, with self-supporting tower, typical loading (2,000 MW)

Table 5. DC electric field levels (kV/m) for Bipole III with self-supporting tower

Load Conditions*		ROW Edge (-33 m)	Profile Peak (within ROW)		ROW Edge (33 m)
Typical Load	Fair (kV/m)	-4.4	-16.6	22.4	6.6
	Foul (kV/m)	-9.5	-30.1	30.1	9.5
Contingency Load	Fair (kV/m)	-4.4	-17.0	22.9	6.6
	Foul (kV/m)	-9.5	-30.8	30.8	9.5
Emergency Load	Fair (kV/m)	-4.3	-19.8	26.3	6.5
	Foul (kV/m)	-9.5	-35.1	35.1	9.5

*Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

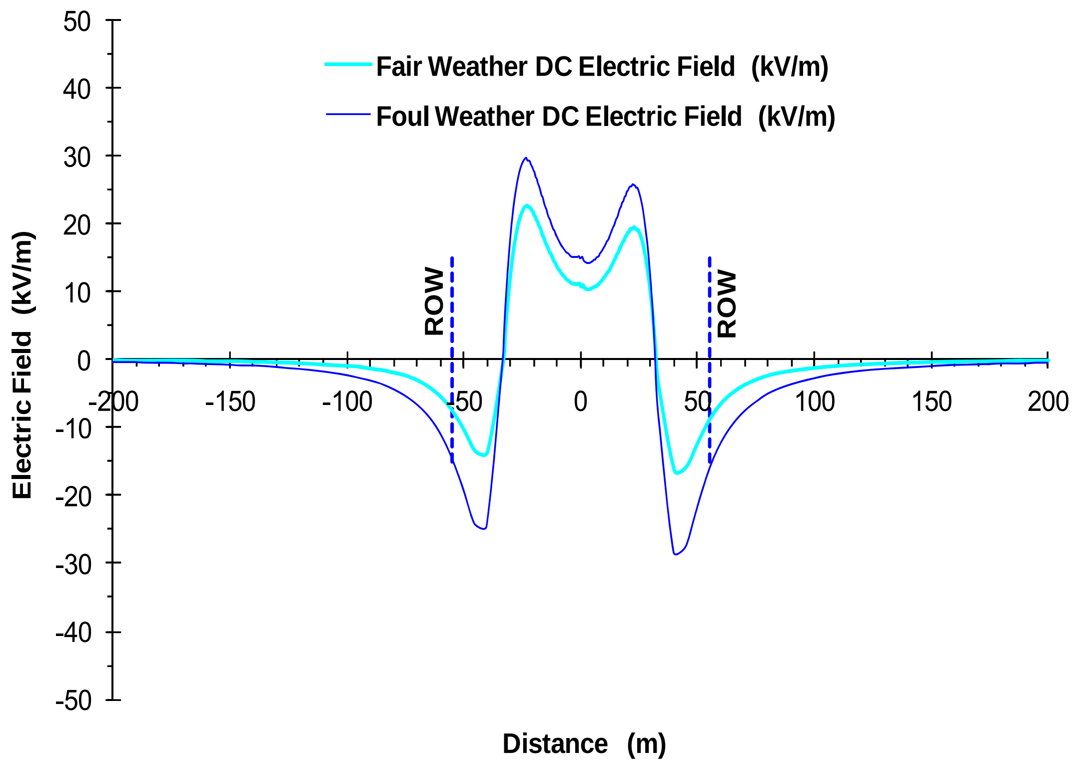

Figure 10. DC electric field profile for Bipole I and II, with guyed tower, typical loading

Table 6. DC electric field levels (kV/m) for guyed tower Bipole I and II

Load Conditions*		ROW Edge (-55 m)	Profile Peak (within ROW)		ROW Edge (55 m)
Typical Load	Fair (kV/m)	-7.6	-16.4	22.6	-8.9
	Foul (kV/m)	-14.4	-28.4	29.7	-16.4

*Typical load - Bipole I = 1,559 MW; Bipole II = 1,681 MW

Audible noise

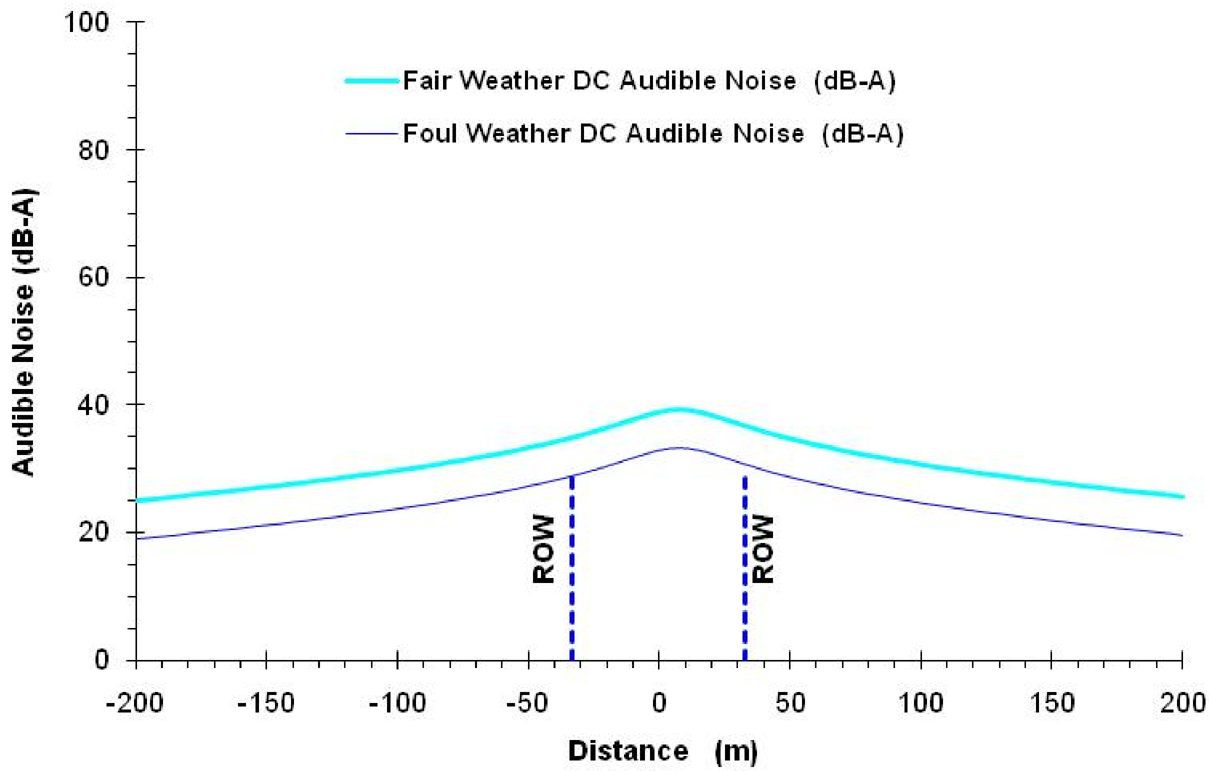

Figure 11. Median AN level in fair and foul weather for Bipole III with guyed tower, typical loading (2,000 MW)

The AN is referenced in dB above 20 μPa with an A-weighting level.

Table 7. Audible noise levels for Bipole III with guyed tower*

Load Conditions†		ROW Edge (-33 m)	Profile Peak (within ROW)	ROW Edge (33 m)
Typical Load	Fair (dB-A)	35.0	39.4	36.8
	Foul (dB-A)	29.0	33.4	30.8
Contingency Load	Fair (dB-A)	35.0	39.4	36.8
	Foul (dB-A)	29.0	33.4	30.8
Emergency Load	Fair (dB-A)	35.1	39.7	36.9
	Foul (dB-A)	29.1	33.7	30.9

*275 m Altitude

†Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

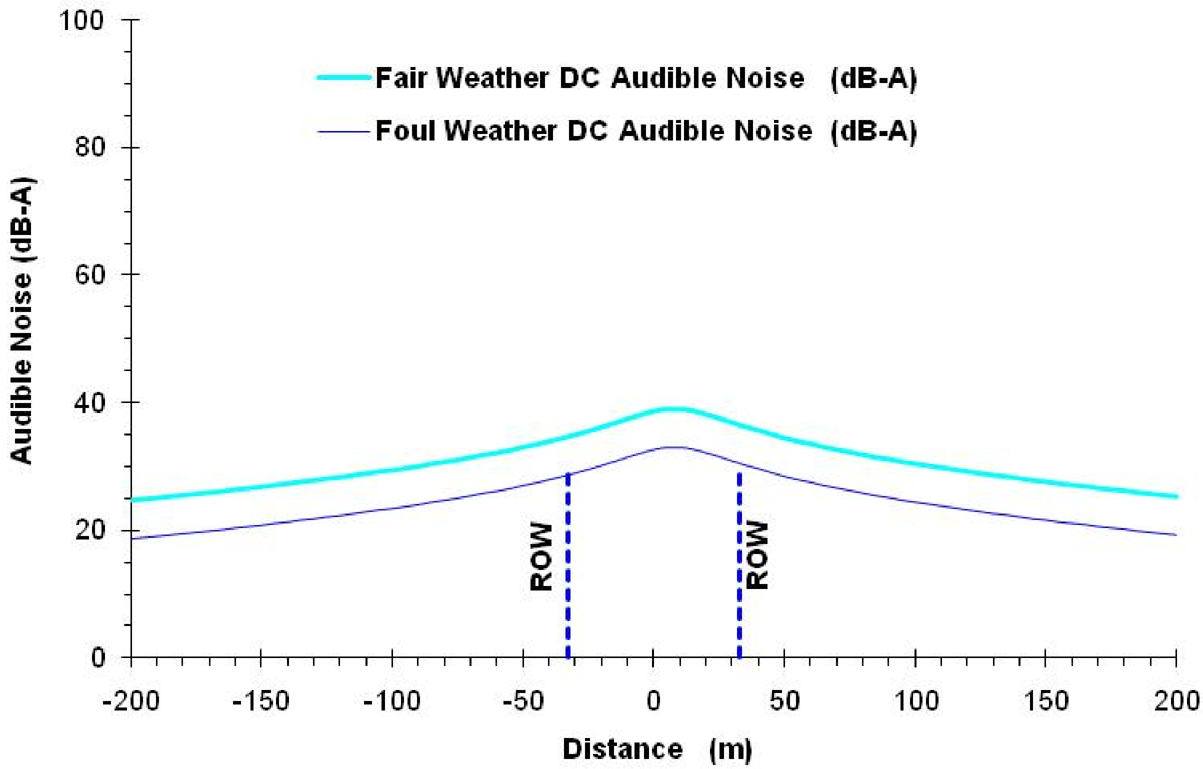

Figure 12. Median AN level in fair and foul weather for Bipole III with self-supporting tower, typical loading (2,000 MW)

Table 8. Audible noise levels for Bipole III with self-supporting tower*

Load Conditions†		ROW Edge (-33 m)	Profile Peak (within ROW)	ROW Edge (33 m)
Typical Load	Fair (dB-A)	34.6	38.9	36.4
	Foul (dB-A)	28.6	32.9	30.4
Contingency Load	Fair (dB-A)	34.6	39.0	36.4
	Foul (dB-A)	28.6	33.0	30.4
Emergency Load	Fair (dB-A)	34.7	39.3	36.6
	Foul (dB-A)	28.7	33.3	30.6

*275 m Altitude

†Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

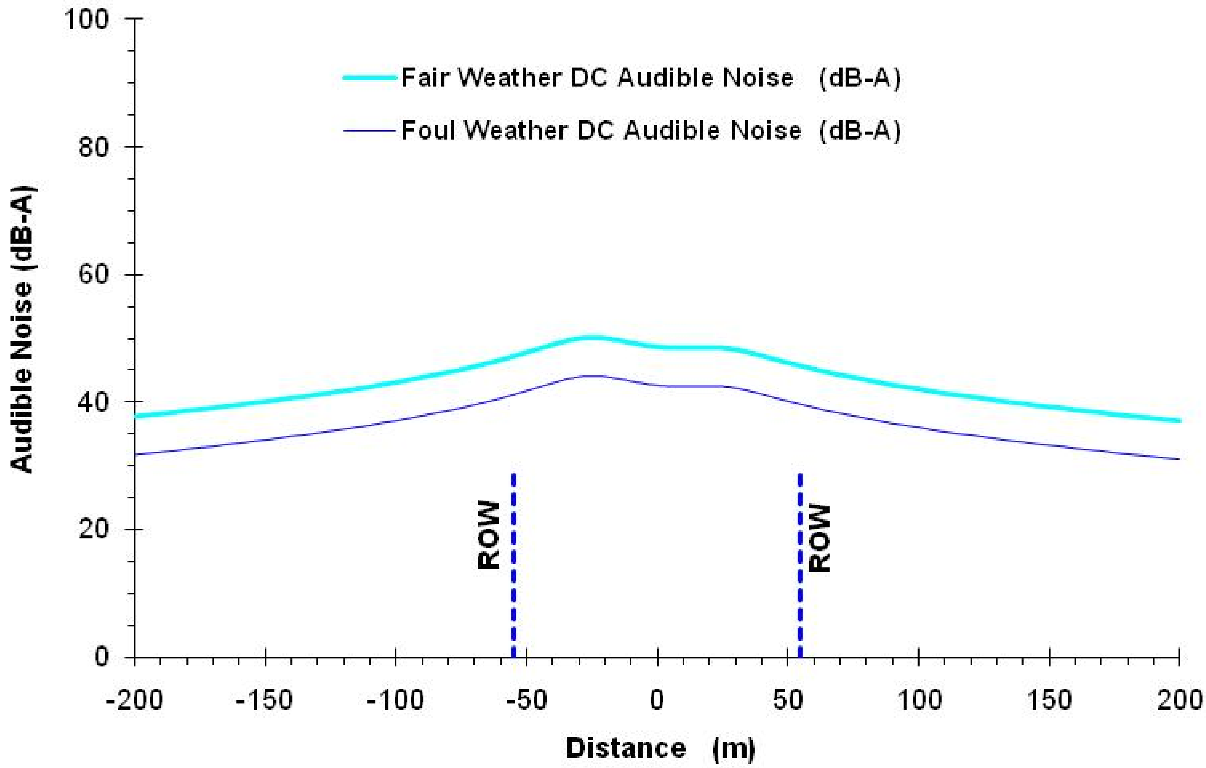

Figure 13. Median AN level in fair and foul weather for Bipole I and II with guyed tower, typical loading

Table 9. Audible noise levels for guyed tower Bipole I and II*

Load Conditions†		ROW Edge (-55 m)	Profile Peak (within ROW)	ROW Edge (55 m)
Typical Load	Fair (dB-A)	47.2	50.1	45.7
	Foul (dB-A)	41.2	44.1	39.7

*300 m Altitude

†Typical load – Bipole I = 1,559 MW; Bipole II = 1,681 MW

Radio noise

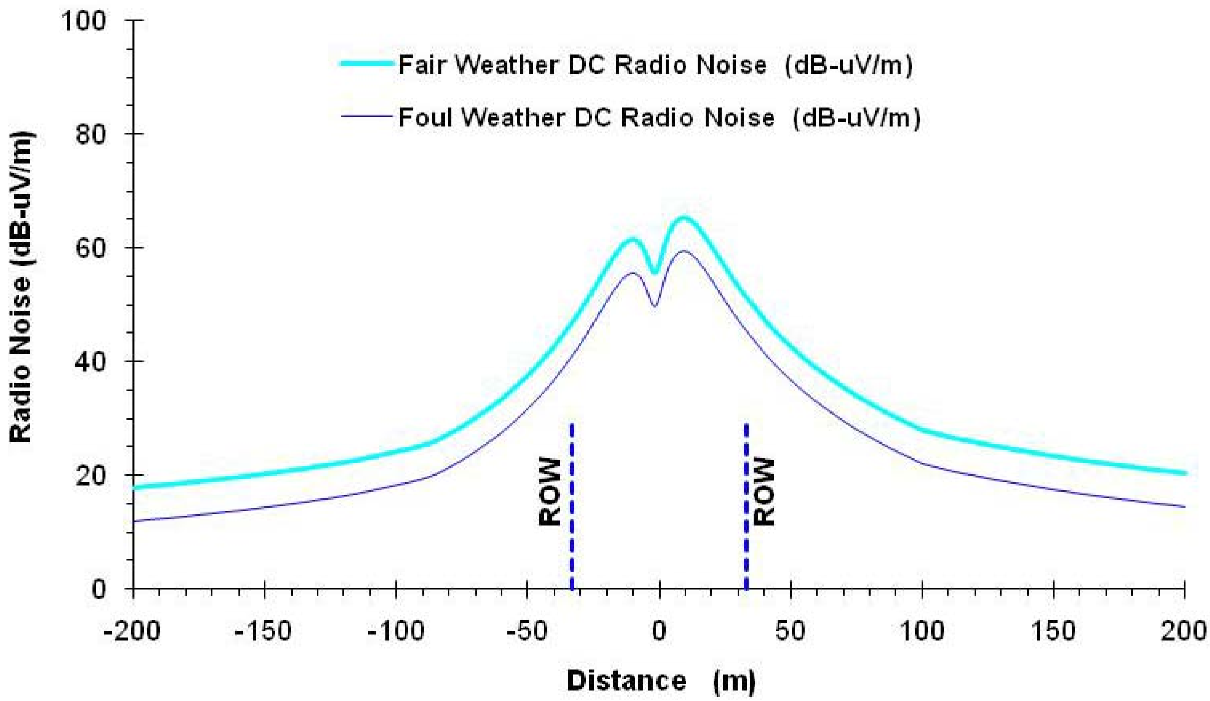

Figure 14. Median RN levels in fair and foul weather for Bipole III with guyed tower, typical loading (2,000 MW)

Table 10. Radio noise levels for Bipole III with guyed tower*

Load Conditions†		ROW Edge (-33 m)	Profile Peak (within ROW)	ROW Edge (33 m)
Typical Load	Fair (dB-µV/m)	47.1	65.4	51.5
	Foul (dB-µV/m)	41.1	59.4	45.5
Contingency Load	Fair (dB-µV/m)	47.0	65.5	51.4
	Foul (dB-µV/m)	41.0	59.5	45.4
Emergency Load	Fair (dB-µV/m)	46.2	66.5	50.7
	Foul (dB-µV/m)	40.2	60.5	44.7

*275m Altitude

†Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

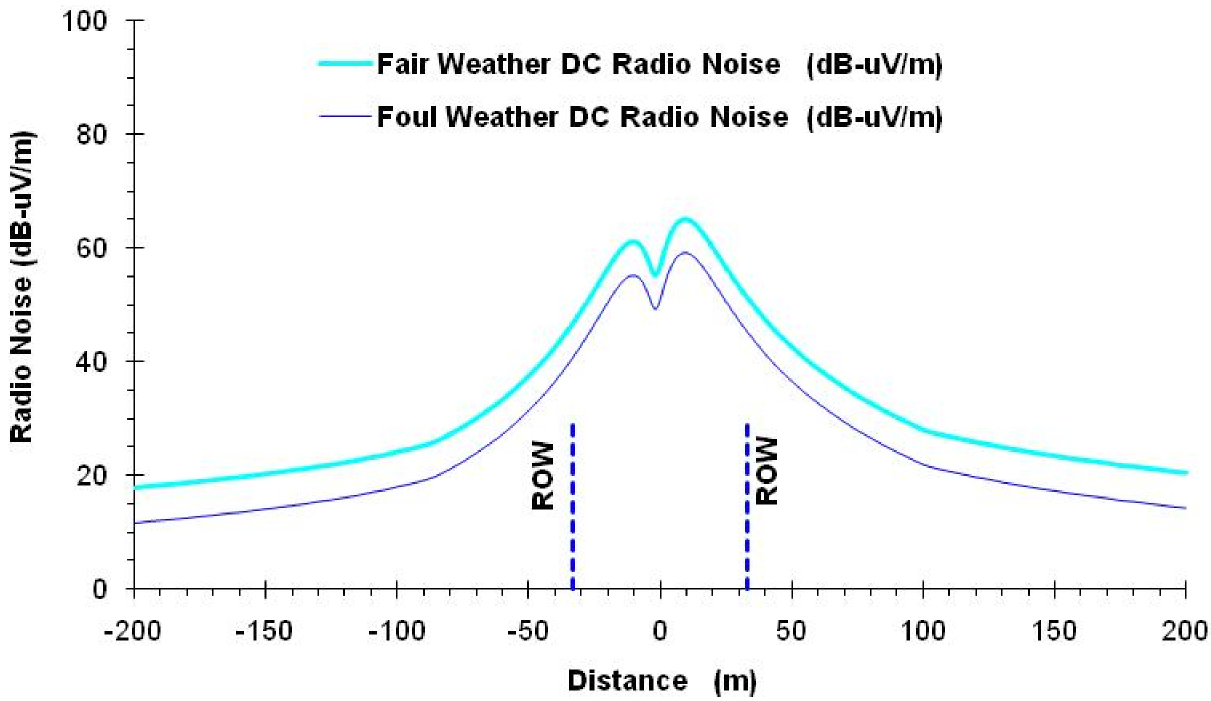

Figure 15. Median RN levels in fair and foul weather for Bipole III with self-supporting tower, typical loading (2,000 MW)

Table 11. Radio noise levels for Bipole III with self-supporting tower*

Load Conditions†		ROW Edge (-33 m)	Profile Peak (within ROW)	ROW Edge (33 m)
Typical Load	Fair (dB-μV/m)	46.9	65.2	51.4
	Foul (dB-μV/m)	40.9	59.2	45.4
Contingency Load	Fair (dB-μV/m)	46.8	65.3	51.3
	Foul (dB-μV/m)	40.8	59.3	45.3
Emergency Load	Fair (dB-μV/m)	46.1	66.3	50.6
	Foul (dB-μV/m)	40.1	60.3	44.6

*275m Altitude

†Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

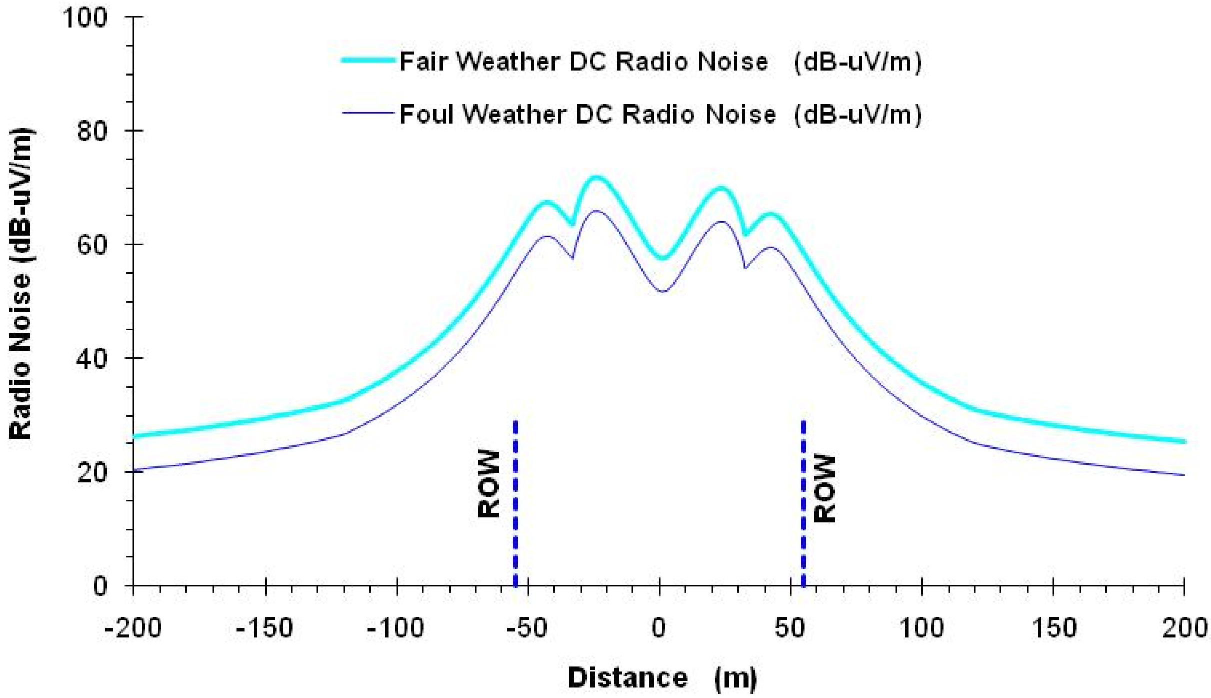

Figure 16. Median RN levels in fair and foul weather for Bipole I and II with guyed tower, typical loading

Table 12. Radio noise levels for guyed tower Bipole I and II*

Load Conditions†		ROW Edge (-55 m)	Profile Peak (within ROW)	ROW Edge (55 m)
Typical Load	Fair (dB-μV/m)	60.7	71.9	58.7
	Foul (dB-μV/m)	54.7	65.9	52.7

*300 m Altitude

†Typical load – Bipole I = 1,559 MW; Bipole II = 1,681 MW

Air ions

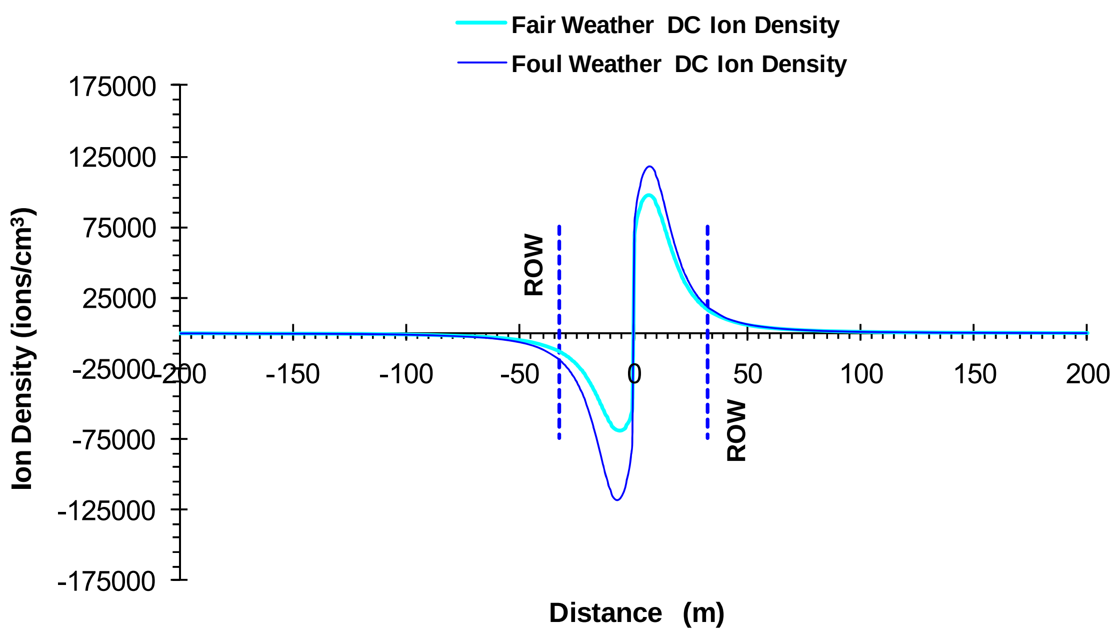

Figure 17. Profile of small ion density levels for Bipole III, with guyed tower, typical loading (2,000 MW)

Table 13. Small ion density levels for Bipole III with guyed tower

Load Conditions*		ROW Edge (-33 m)	Profile Peak (within ROW)		ROW Edge (33 m)
Typical Load	Fair (ions/cm^3)	-12,449	-68,548	97,145	16,008
	Foul (ions/cm^3)	-18,194	-118,144	118,144	18,194
Contingency Load	Fair (ions/cm^3)	-12,625	-70,675	100,283	16,195
	Foul (ions/cm^3)	-18,382	-122,078	122,078	18,382
Emergency Load	Fair (ions/cm^3)	-13,065	-87,602	124,810	16,606
	Foul (ions/cm^3)	-18,764	-152,509	152,509	18,764

*Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

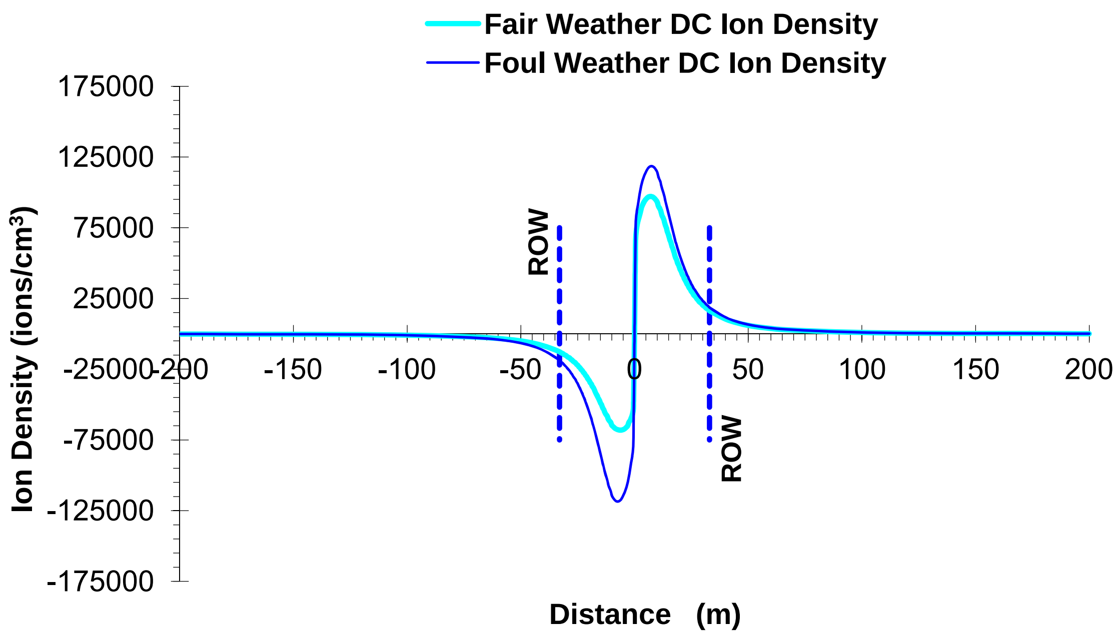

Figure 18. Profile of small ion density levels for Bipole III with self-supporting tower, typical loading (2,000 MW)

Table 14. Small ion density levels for Bipole III with self-supporting tower

Load Conditions*		ROW Edge (-33 m)	Profile Peak (within ROW)		ROW Edge (33 m)
Typical Load	Fair (ions/cm^3)	-12,603	-68,044	97,174	16,310
	Foul (ions/cm^3)	-18,589	-118,582	118,582	18,589
Contingency Load	Fair (ions/cm^3)	-12,791	-70,112	100,254	16,510
	Foul (ions/cm^3)	-18,791	-122,489	122,489	18,791
Emergency Load	Fair (ions/cm^3)	-13,253	-87,158	124,982	16,945
	Foul (ions/cm^3)	-19,198	-153,189	153,189	19,198

*Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

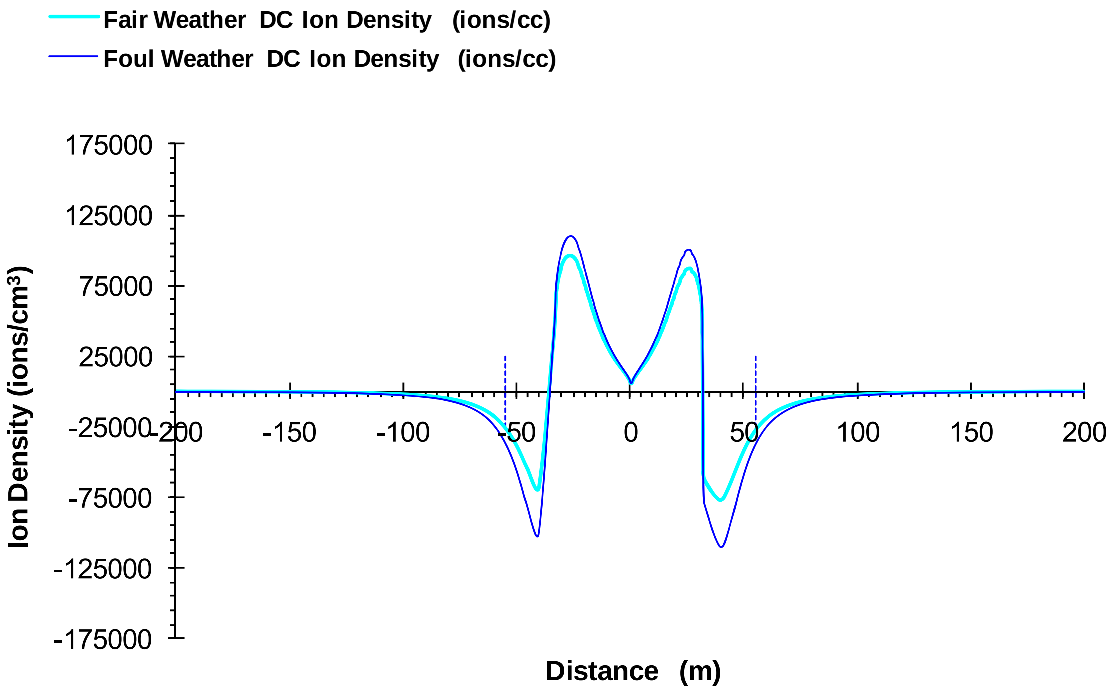

Figure 19. Profile of small ion density levels for Bipole I and II, typical loading

Table 15. Small air ion levels for guyed tower Bipole I and II

Load Conditions*		ROW Edge (-55 m)	Profile Peak (within ROW)		ROW Edge (55 m)
Typical Load	Fair (ions/cm^3)	-25,658	-76,879	95,623	-28,828
	Foul (ions/cm^3)	-35,496	-109,886	109,886	-38,694

*Typical load – Bipole I = 1,559 MW; Bipole II = 1,681 MW

Ion current density

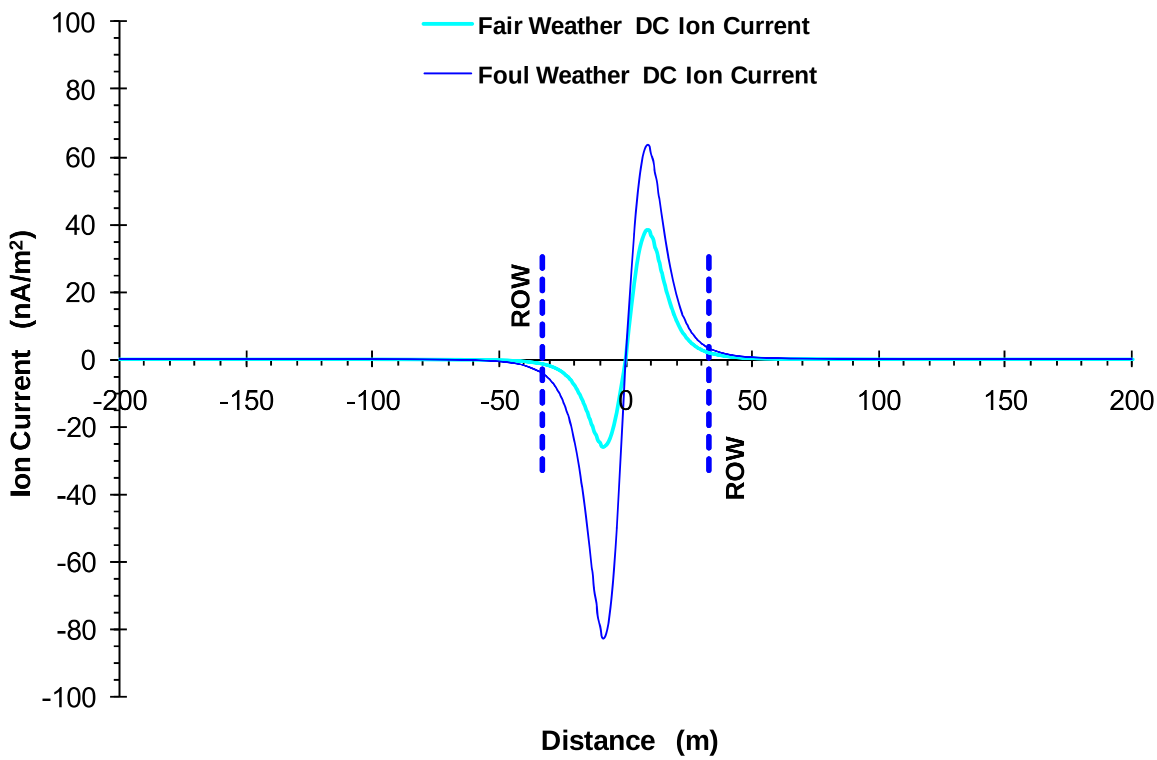

Figure 20. Profile of ion current density for Bipole III with guyed tower, typical loading (2,000 MW)

Table 16. Ion current density for Bipole III with guyed tower

Load Conditions*		ROW Edge (-33 m)	Profile Peak (within ROW)		ROW Edge (33 m)
Typical Load	Fair (nA/m^2)	-1	-26	39	2
	Foul (nA/m^2)	-4	-83	63	3
Contingency Load	Fair (nA/m^2)	-1	-28	41	2
	Foul (nA/m^2)	-4	-87	67	3
Emergency Load	Fair (nA/m^2)	-1	-40	58	2
	Foul (nA/m^2)	-4	-124	95	3

*Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

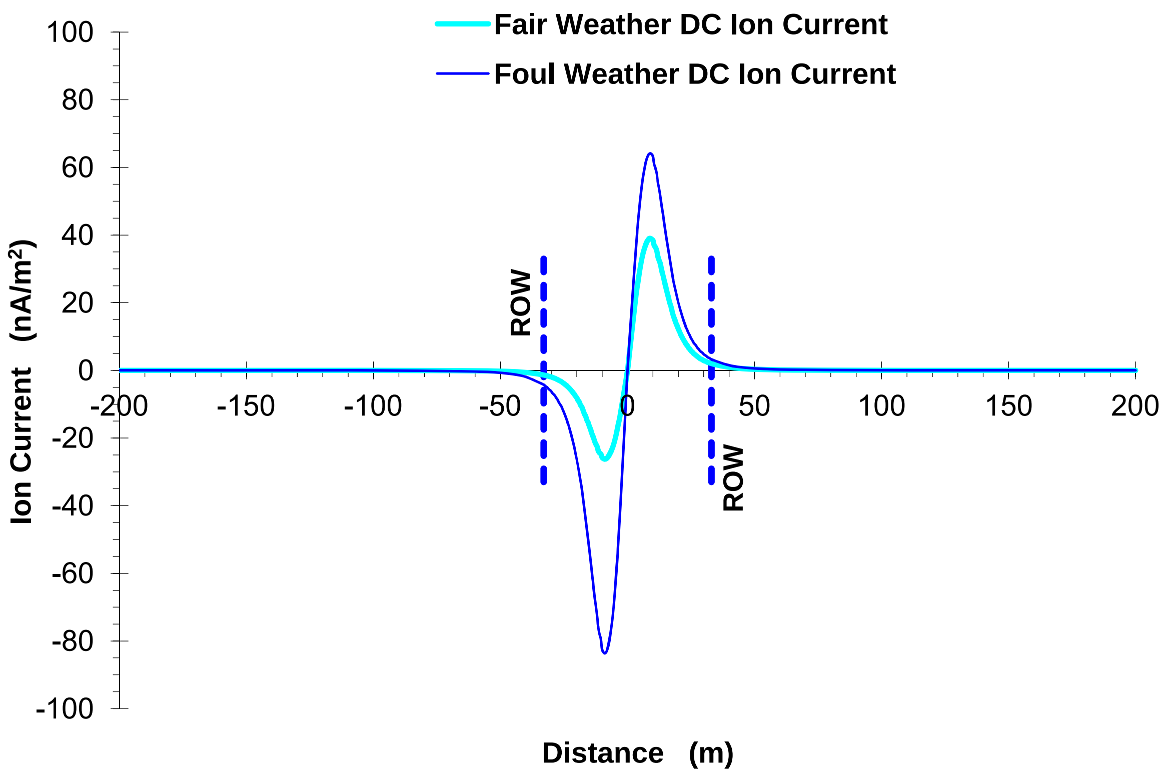

Figure 21. Profile of ion current density for Bipole III with self-supporting tower, typical loading (2,000 MW)

Table 17. Ion current density for Bipole III with self-supporting tower

Load Conditions*		ROW Edge (-33 m)	Profile Peak (within ROW)		ROW Edge (33 m)
Typical Load	Fair (nA/m^2)	-1	-26	39	2
	Foul (nA/m^2)	-4	-84	64	3
Contingency Load	Fair (nA/m^2)	-1	-28	41	2
	Foul (nA/m^2)	-4	-88	68	3
Emergency Load	Fair (nA/m^2)	-1	-40	59	2
	Foul (nA/m^2)	-4	-127	97	3

*Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

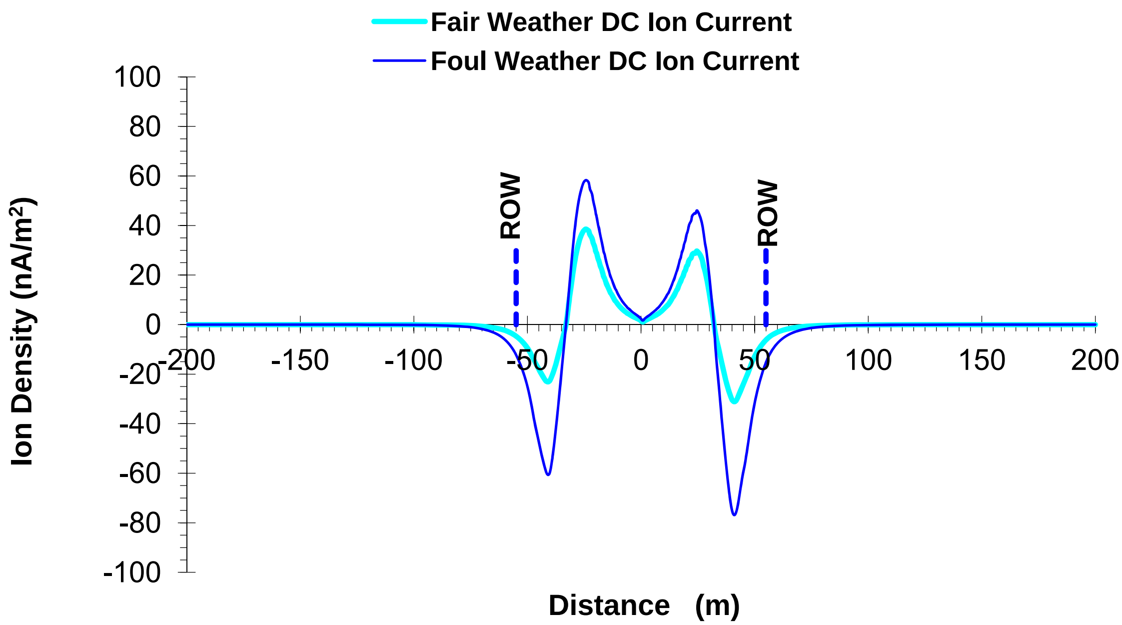

Figure 22. Profile of ion current density for Bipole I and II, typical loading

Table 18. Ion current density levels for guyed tower Bipole I and II

Load Conditions*		ROW Edge (-55 m)	Profile Peak (within ROW)		ROW Edge (55 m)
Typical Load	Fair (nA/m^2)	-5	-30	39	-6
	Foul (nA/m^2)	-12	-75	58	-15

*Typical load – Bipole I = 1,559 MW; Bipole II = 1,681 MW

Table 19. Comparison of the design and electrical characteristics of the proposed Bipole III line and existing overhead DC transmission lines

Transmission Line	(kV)	Line Ht (m)	Pole Sep (m)	Cond. Bundle (mm)	Conductor Gradient (kV/cm)	Profile Peaks* Median Electric Field (kV/m)/Median Small Ion (per cm^3) Fair Weather	Foul Weather	(-) Ion Current Density (nA/m^2) Fair Weather	Foul Weather
Bipole III DC Line (Figure 1) [Self-supporting Tower]	±500	13.2	15.5	3x38	22.2	22 / 97,000	30 / 119,000	39	-84
Bipole III DC Line (Figure 2) [Guyed Tower]	±500	13.2	15.0	3x38	22.4	22 / 97,000	30 / 118,000	39	-83
Bipole I (Figure 3)	±463	13.5	13.4	2x41	25.5	23 / 96,000	30 /110,000	39	-75
Bipole II (Figure 3)	±500	13.5			27.0				
DC Pacific Intertie-initial *Oregon/California*	±400	9.8	12.2	2x46	20.9	23 / 141,000	32 / 175,000	60	-135
CPA-UPA *North Dakota*	±400	10.7	12.2	2x38	24.1	23 / 125,000	30 / 148,000	53	-107
DC Pacific Intertie-upgrade *Oregon/California*	±500	9.8	12.2	2x46	26.1	34 / 199,000	45 / 231,000	125	-191
Intermountain Power *Nevada*	±500	12.2	12.8	3x39	20.5	22 / 105,000	30 / 135,000	43	-76
New Eng-Hydro Québec *Vermont*	±450	12.2	13.7	3x51	16.8	18 / 80,000	25 / 112,000	27	-67

*Electric fields rounded to the closest 10 kV/m and ion density rounded to the closest 100,000 ions/cm^3

4. Comparison of Bipole III and Bipole I/II Electrical Environments

It is difficult to succinctly compare the electrical environment of the proposed Bipole III line with the Bipole I/II lines because of the large number of profiles and tables presented above. Figure 23 compares the relative levels of electric field, magnetic field, air ions, ion current density, AN, and RN on the ROW and at the edge of the ROW from these lines. Note that the distance from the centerline of the Bipole III line to the ROW edges is 33 m, whereas the distance from center line of the nearest Bipole I or II structure to the edge of the ROW is 22.5 m. The peak values of calculated electric fields, air ions, and ion current density are very similar. The peak magnetic field of Bipole I/II is lower because slightly lower typical loads (Bipole I = 1,559 MW; Bipole II = 1,681 MW) were assumed than were used for Bipole III (2,000 MW). The peak values of AN and RN are lower on the ROW and at the edge of the ROW for Bipole III than Bipoles I and II. This occurs largely because the surface gradient of the three-conductor bundle of Bipole III is lower than the surface gradient of the two-conductor bundles of Bipole I/II.

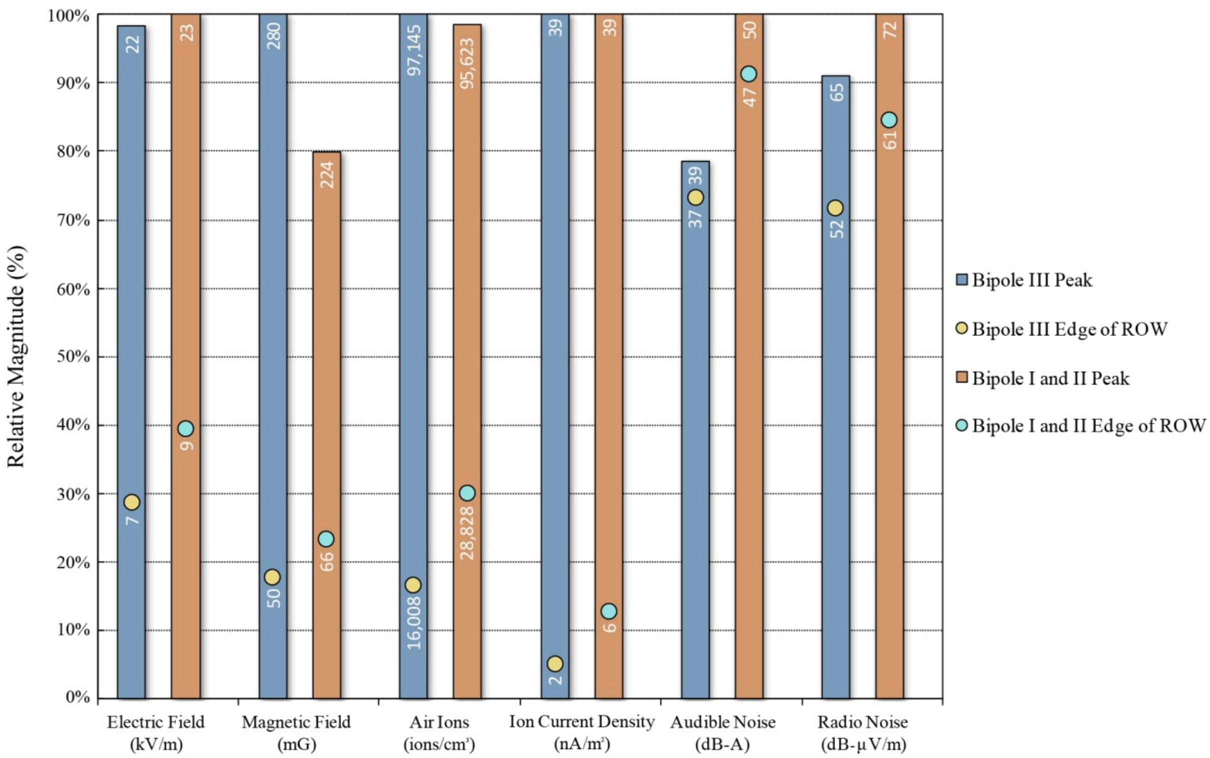

Figure 23. Modeled electrical parameters at typical loading for Bipole III and Bipole I/II guyed tower configurations

5. Ground Electrode/Electrode Line

The converter station is grounded by a low-voltage electrode line to a buried electrode. The possibility of effects associated with the electric and magnetic fields from the electrode and the electrode line are discussed below.

Ground Electrode

A remote ground electrode will be installed to correct small current imbalances between the positive and negative conductors and during abnormal operating conditions. The electrode also is expected to be used in a monopolar operating mode to maintain power transfer on an emergency basis if a problem with a valve group or one of the conductor bundles is out of service. Based on historical data on Bipoles I and II, a long-term outage rate of about 8% is projected for one pole or the other due to maintenance or other outages. Most of the outages on Bipoles I and II have involved valve groups or maintenance and the design of Bipole III allows for such operations without the use of the ground electrode. Hence, the need for full power return over the Bipole III electrode would be even less than for Bipoles I and II and would primarily be limited to maintain power transfer only if the line conductors associated with the outed pole were not available for use. The ground electrode is designed to operate at a continuous current of 2,000 amperes (A) and at higher currents up to 2,750 A for a more limited period. The ground potential rise (GPR) at the neutral bus in the converter terminals will be low under all operating conditions; however, DC characteristic and non-characteristic harmonic current flows through the neutral conductors must also be considered. Thus, for touch and step potential considerations, the neutral bus must be classified as a high voltage conductor.

The electrode, as planned, is a ring electrode with a diameter between 350 and 650 m (the exact diameter will depend on the final design). The ring will be fed from a power pole placed in the center of the ring at which the electrode line will be terminated as shown in Figure 24. Four cable circuits will be placed with 90 degree separations to connect the electrode line to the ring electrode. Disconnect switches will be placed on the pole used for the line termination to enable interruption of the current flowing to segments of the ring.

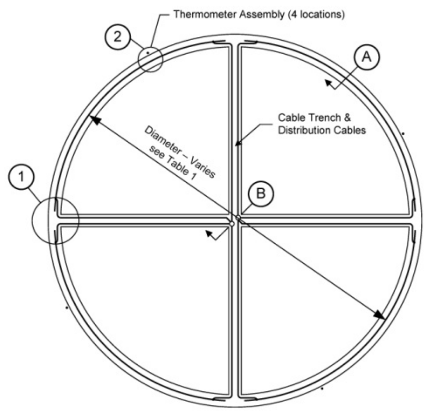

Figure 24. Schematic diagram showing overhead view of buried ground electrode

The electrode line from the converter station terminates at the center of the ring

The connections between the ring electrode and the electrode line termination at the center of the ring will be though four pairs of cables at 90 degree spacing. If the currents are balanced, the current in each of the eight cables will be approximately 350 A if the electrode line current is 2,750 A. These cables are assumed to be buried 0.6 m deep. If a person is standing on top of the two cables when they are conducting about 350 A_{dc} each, the resulting magnetic field (away from the electrode line's termination pole) will be less than 1,000 mG at 1 m above ground.[5] At the termination pole in the center of the electrode (Figure 25) the magnetic field might be 5 to 10 Gauss (G) close to the pole during emergency monopole operation.

[5] This assumes that the magnetic field is the result of only the current in the cables. If the person is standing under the incoming electrode line, the fields will be approximately double (see Figure 29).

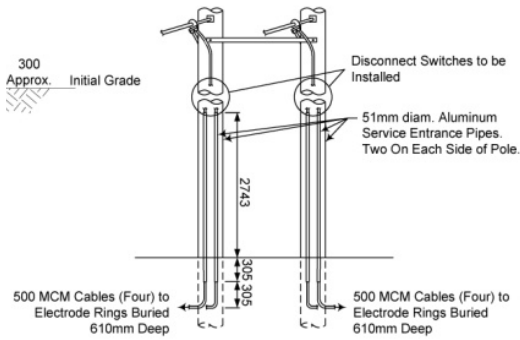

Figure 25. Termination of the electrode line at pole at the center of the ring electrode and transition to underground cable

The magnetic fields to which a person would be exposed standing on top of the electrode ring will depend on where the person is standing along the periphery of the ring. The current flowing from the electrode into the ground can be assumed to be uniformly distributed with vertical and tangential (horizontal) current components. The currents flowing in the cables that form the contact between the electrode material and the conductor imbedded in the electrode will have a maximum level close to the electrode infeed (contact) points and the currents flowing in the electrode cables will be concentrated in the insulated cables. Although closed form solutions for calculating the fields can be used (Uhlmann, 1975), a numerical solution would be most useful for mapping the fields. The fields should be lower at all points within the electrode area, however, than the fields directly above the electrode cables discussed above. The far-fields some distance away from the ground electrodes will depend on the local geology, and to calculate these fields would require a detailed map of the soil resistivity.

The step potentials to which personnel will be exposed when walking across the electrode sites during emergency operation have been calculated (Teshmont, 2010; 2011). The step potentials are between approximately 5 volts/metre (V/m) and 10 V/m. The calculations have been made assuming normal soils without any consideration for soil resistivity variations as a function of season. The type of soil and the resistivity of the soil have a significant influence on the step potential. The resistivity is strongly correlated with the moisture content and temperature of the soil (Morgan, 1993). Frozen soils have very high resistivity, which should tend to increase the resistance of the electrode by reducing the volume of low resistance soil surrounding the electrode material. Thus, the resistivity of soils is a highly complex issue but of significant importance when assessing safety issues. Therefore, even though the electrodes themselves are intended to be installed below the frost zone, the current distribution around the electrodes can be affected if the soil is frozen. Since the resistivity can be an order of magnitude or higher if the soil is frozen, a calculation assuming frozen soil should be performed during final design.[6]

The step potentials have been calculated assuming steady-state current flow into the electrode during monopolar operation.[7] This is for the most part conservative. When a short circuit from a pole to ground occurs, however, the current can increase to two or three times the normal current. The instantaneous current change is limited by the pole to ground surge impedance, which means that the current will rise by about 1.5 kiloampere (kA) on the faulted conductor. This current will flow through the electrode line to the converter station. The current control system in the rectifier station should limit the overcurrent, but the actual peak current and the duration of this peak current depends on the speed of response of the control system. That is, the electrode current could change by about 3 to 4 kA. During the interval when the failed pole is de-energized to enable clearing of the fault, the other pole will operate with full current through the electrode. Upon restart of the faulted pole and assuming that the fault is cleared, normal bipolar operation will be resumed with low or insignificant electrode current flow. The peak fault current might last for 20 to 50 milliseconds. That is sufficiently long to have an effect on the step potentials to which people or animals might be exposed. Therefore, the step potentials should also be calculated for fault conditions.

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6 When the temperature is below freezing, water injection into the soil is probably not practical. Replenishing the water around the electrodes under these conditions, however, might be warranted since the soil around the electrode will not be wetted by rain water for as long as the soil remains frozen.

7 No touch potentials have been calculated. If the electrode is conducting current and if someone drives a vehicle or some machinery out over the electrodes, however, a person contacting the truck or machinery will be exposed to touch potentials that could be significantly higher than the step potentials under similar conditions. The risks associated with touching conducting objects on the electrode sites should, therefore, be assessed.

Injection of 60-Hz currents from a converter should also be considered. This can happen as a result of commutation failures in the inverter end of the line or as a result of valve misfires. These alternating current (AC) injections will probably have less effect on the electrode current flows than a pole to ground fault although commutation failures are associated with overcurrents and also at times lead to current zeros in the line current of the affected pole. In that case, the direct current will go to zero and the system will recover from this condition after some time.

Drying out of the electrodes could lead to a thermal run-away of the electrodes. This could in theory lead to overheating and even pyrolysis (thermal degradation) of the coke typically used around the electrodes. The resistance of the electrode would, however, have to increase significantly prior to electrode dry-out. Therefore, it should be possible to detect the increasing electrode resistance prior to the thermal runaway by monitoring the GPR between the electrode line and the station ground mat. The best remedy to avoid dry-out of the electrodes is to keep the electrodes wet, although this might not be easy to do during winter conditions with frozen soils.

Step potentials for most animals walking across the electrode site will be even lower than for a person because of their shorter strides, but for large animals, such as a moose at stand-still, the step potentials could be two to three times higher than for people. However, at the same time, the recommended limits for large animals are more than twice those for people (IEC, 2007).

A small stream is about 800 m from the northern boundary of the site for the ground electrode. The potential experienced by fish in this stream during operation of the ground electrode was estimated. The site for the ground electrode is a square plot of land approximately 1.6 km on each side. To simplify the computations, the ground electrode was assumed to be located at the center of this square. It was also assumed that no current flows inwards towards the center of the electrode area. End effects were ignored by assuming that the electrode extends infinitely in length with a uniform current density to a depth equivalent to the distance of the stream from the nearest edge of the ground electrode ring. In the absence of detailed information, the soil was assumed to be uniform at least up to a depth also equivalent to the distance of the stream from the nearest edge of the ground electrode ring. The electric field experienced by a fish in a shallow stream 800 m from the edge of the ground electrode site (1.6 km x 1.6 km) with a buried ring electrode that has a 650 m radius centered in the site can be estimated from the following assumptions and expression:

- Cylinder 1,600 m in radius and 950 m deep with area (A_{cyl})
- Current (I) = 2,750 A assuming uniform current distribution and no end effects
- Assumed uniform soil resistance $\rho = 150\ \Omega \cdot m$

Electric field = $I/A_{cyl} \times \rho$ = 43 mV/m

This electric field level is much lower than the quasi-static electric field that is reported to be detected by large Russian sturgeons, which have specialized receptors for electric fields (Basov, 1999), and the detection threshold for smaller fish would be even lower.

Overhead Electrode Line

Like the electrical service in a residence, the Bipole III converter stations require an electrical connection to the ground. For DC transmission systems, an overhead electrode line that will connect the converters to a ground electrode will extend about 9 km from the Keewatinoow converter station and about 15 km from the Riel converter station. The electrode line will consist of two conductors supported by a single-pole wood structure and an overhead shield wire to protect against lighting strikes and protection systems will be installed for fault detection and clearing. Figure 26 depicts the two ground electrode lines connected to the neutral buses at both ends of Bipole III between poles 1 and 2.

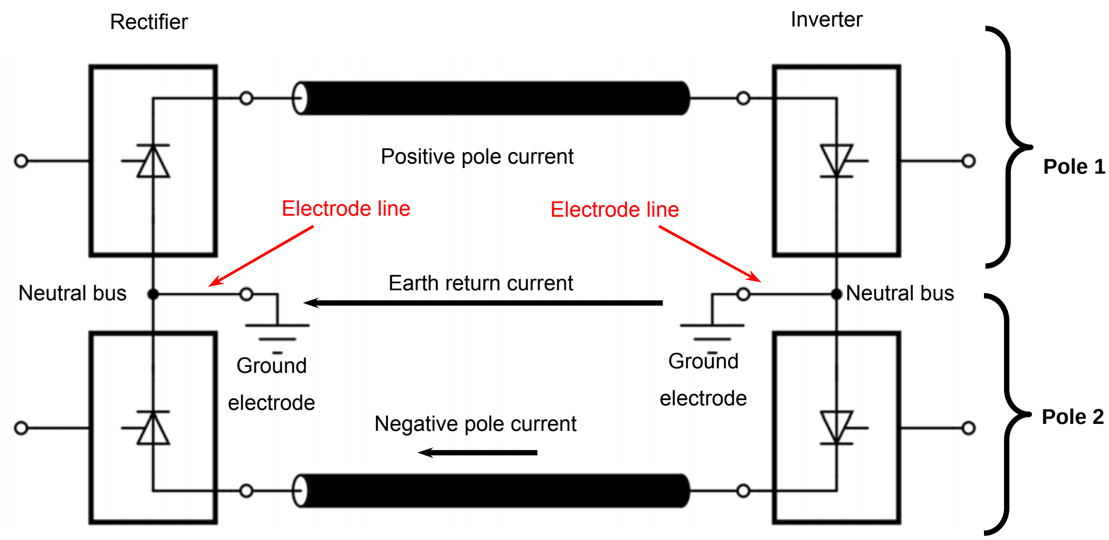

Figure 26. Schematic circuit of the Bipole III circuit showing overhead electrode lines

Remote siting prevents earth return currents from interfering with converter transformers and other station gear. The grounding conductors that connect the station neutrals to the remote ground electrodes are labeled as electrode lines and are highlighted in Figure 26. Bipole III has two electrode lines, one connected to the northern electrode and the other connected to the southern electrode.

At both converter stations AC power is rectified, transmitted as DC power along the two Bipole III conductor bundles, and inverted to AC power at the load. During balanced operation, current on the positive pole equals the current on the negative pole, and no or very small currents flow through the earth return. Unbalanced current flows between the ground electrodes and along the electrode lines, between the station neutrals, can occur. The electrode lines normally carry a small current (< 110 A) to compensate for normal current imbalance between the two Bipole III conductor bundles, but can carry a monopolar design load of 1,000 MW (2,000 A). Another design option evaluated by Teshmont was continuous current of 2,500 A and 60 days of operation at 2,750 A. The higher short-term loading (2,750 A) was assumed for the stream model to assess electric field exposures of fish in a stream described above. The monopolar operational modes using the ground electrode would only occur in unusual or emergency conditions, e.g., when one of the two Bipole III conductor bundles is out of service.

The northern and southern electrode lines are similar in appearance to an ordinary low-voltage AC distribution line, as shown in the representative design in Figure 27. At tangent locations, the electrode lines will be supported on 40-50 foot wood poles carrying two conductors each 1-inch in diameter.

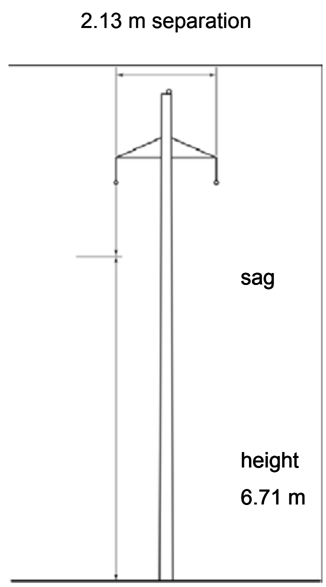

Figure 27. Representative design of the structure of the north and south electrode lines

During bipole operation, the electrode lines will produce electric or magnetic fields far smaller than those in the vicinity of the Bipole III conductors. The total magnetic field around the electrode line during normal bipole operation, including the effect of the geomagnetic field is depicted in Figure 28.

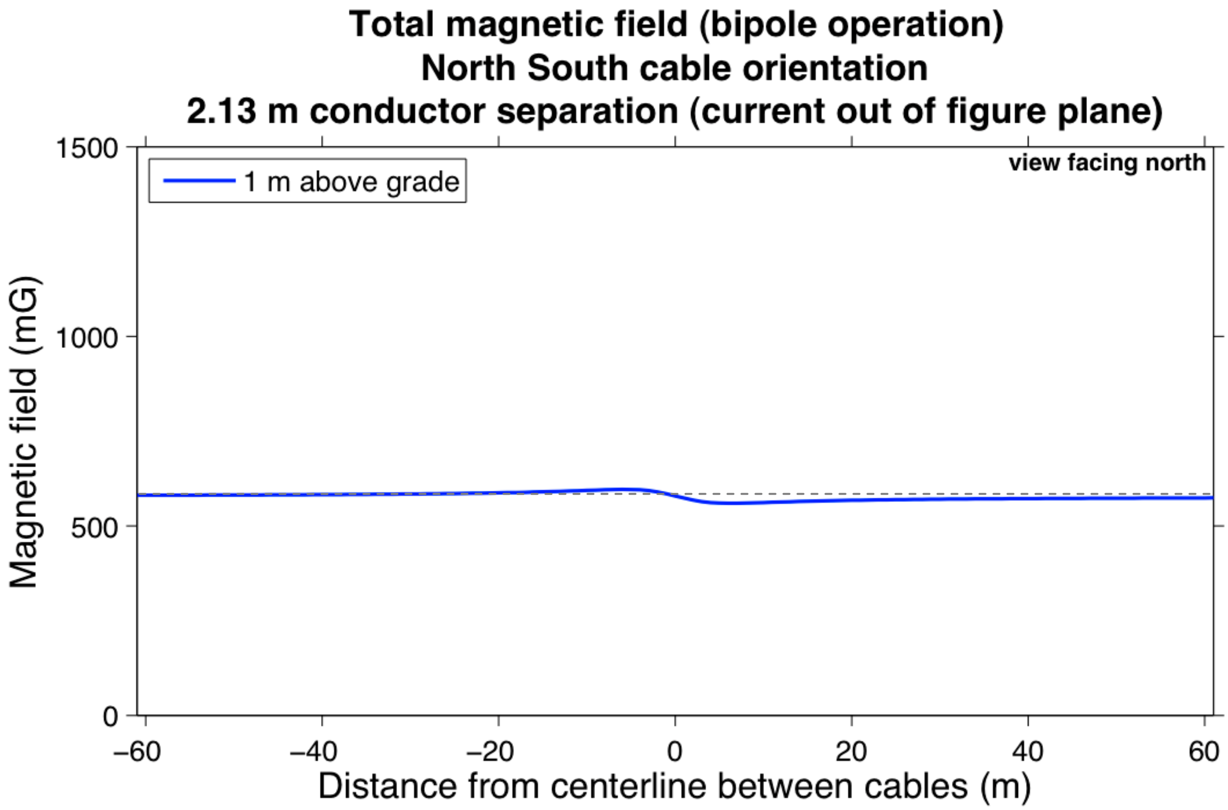

Figure 28. Total DC magnetic field (geomagnetic+electrode line) during bipolar operation of the Bipole III transmission line

In the depicted profile, the electrode line is oriented north-south and carries southbound current (110 A). The dashed line indicates the level of the geomagnetic field alone.

Calculated magnetic fields for other directions of current flow are summarized in Tables 20 and 21.

Table 20. Deviation of total DC magnetic field (cables + geomagnetic) from 577 mG, for north-south orientation of electrode line

Operating condition	Current direction	Offset from centerline*					
		-100 m	-50 m	max + deviation	max – deviation	+50 m	+100 m
bipole	north	-2.1	-4.2	18.3	-18.3	4.2	2.1
	south	2.1	4.2	18.9	-17.7	-4.2	-2.1
monopole (emergency)	north	-48.1	-94.9	555.5	-272.2	95.9	48.3
	south	48.4	96.2	566.5	-262.4	-94.5	-48.0

*Positions are reported for view facing north (-west +east)

Table 21. Deviation of total DC magnetic field (cables + geomagnetic) from 577 mG, for east-west orientation of electrode line

Operating condition	Current direction	Offset from centerline*					
		-100 m	-50 m	max + deviation	max – deviation	+50 m	+100 m
bipole	east	-2.1	-4.1	23.9	-13.9	4.3	2.2
	west	2.1	4.1	14.4	-23.4	-4.3	-2.2
monopole (emergency)	east	-47.2	-91.2	646.3	-205.6	98.5	49.0
	west	47.6	93.6	474.7	-382.5	-98.1	-48.8

*Positions are reported for view facing east (-north +south)

When needed in an emergency, monopole operating current will flow on the electrode lines and change the existing magnetic field near the line as shown in Figure 29. In any condition, the calculated electric field 1 m above ground is below 0.7 kV/m at a 7.5 kV potential (the maximum anticipated potential) as shown in Figure 30. The ground electrode line will not be a significant source of corona-generated AN or RN because of its low voltage.

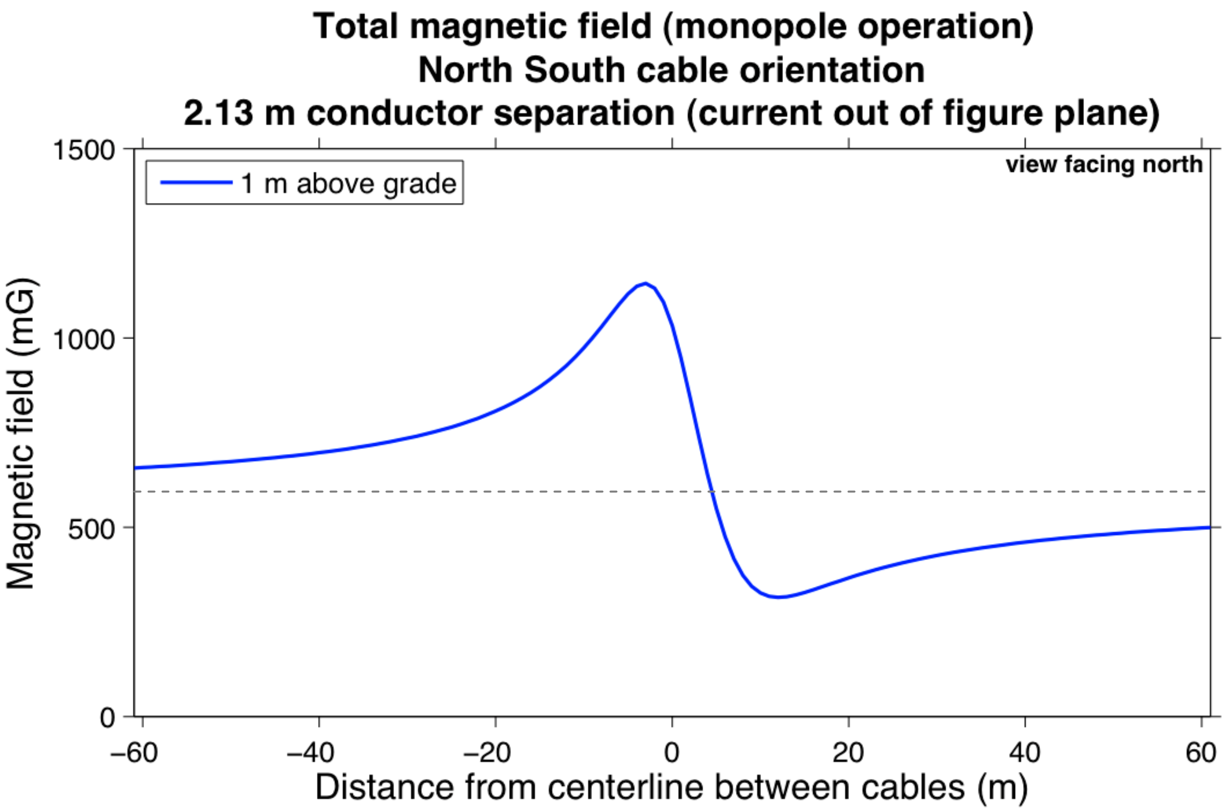

Figure 29. Total DC magnetic field (geomagnetic+electrode line) during emergency monopolar operation of the Bipole III transmission line

In the depicted profile, the electrode line is oriented north-south and carries southbound current (2,500 A). The dashed line indicates the level of the geomagnetic field alone.

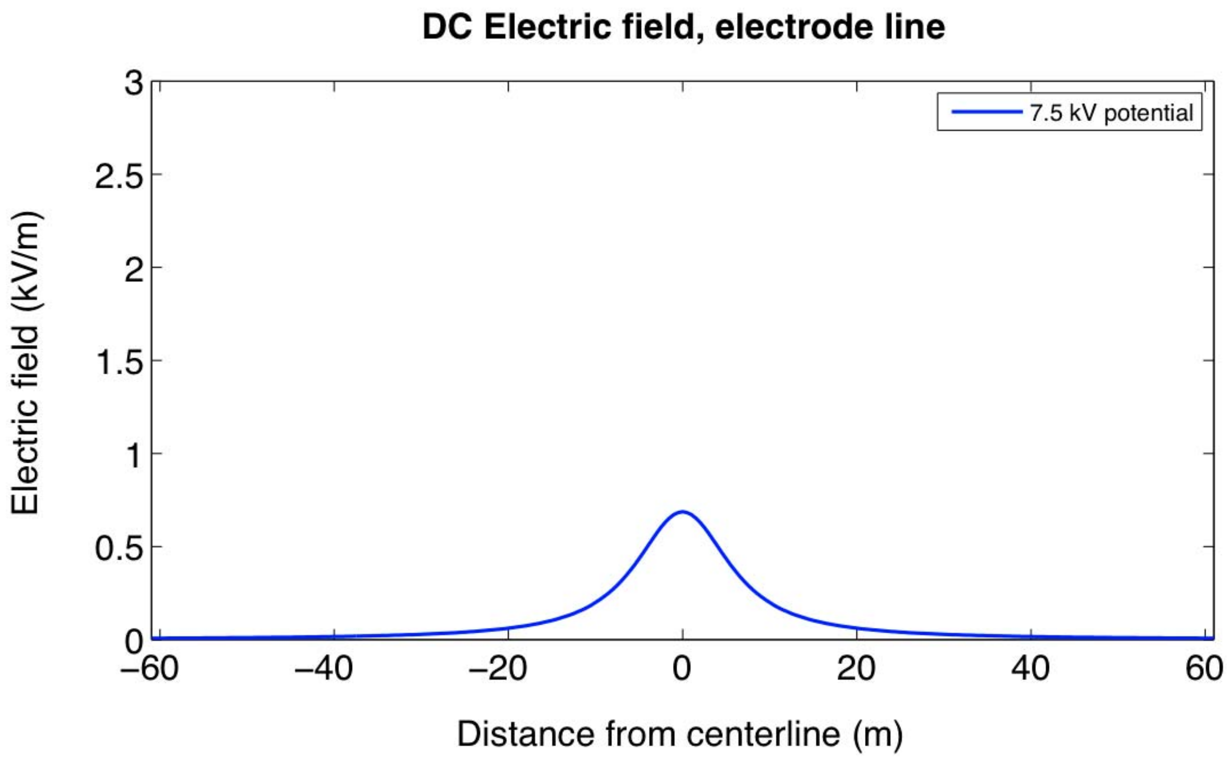

Figure 30. Calculated DC electric field profile for the electrode line at 7.5 kV potential

AC Harmonic currents

A DC bipole consists of a number of 6-pulse converter groups connected in series as shown in simplified form in Figure 31. The electrode lines are typically brought out from the terminals to a remote location where the land electrodes are located to avoid injecting DC currents into the converter stations' ground grid.

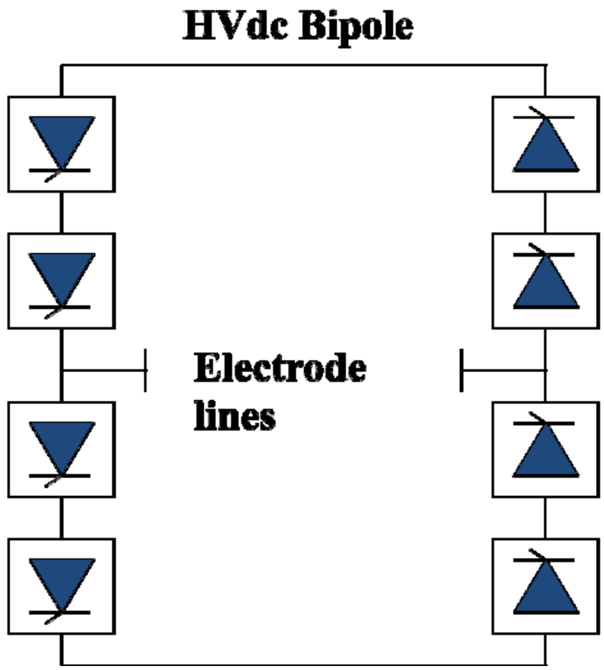

Figure 31. DC Bipole configuration showing 6-pulse converter groups and electrode lines

If two 6-pulse groups are connected in series as shown in Figure 32, and one is fed from a Y-Y connected transformer and the other via a Y-Delta connected transformer, the output voltage from the converter will mainly contain 12-pulse harmonics and multiples thereof (Reeve and Baron, 1970; Lasseter et al., 1977; Mathur and Sharaf, 1983). These are the so-called “characteristic harmonic voltages.” The harmonic voltages generated in these converters are partially blocked by a smoothing reactor normally placed between the converter groups and the DC line conductors. Harmonic filters, which further attenuate the harmonic voltages, are typically installed to filter out these harmonics from the DC voltage as it enters the line as shown in Figure 33 (Adamson et al., 1983; Garrity et al., 1989). Improved filtering can also be achieved by using active filtering systems (Zhang et al., 1993). It is important that the DC filters are connected to the neutral bus, otherwise the harmonic currents would flow back to the converter station through the electrode line. It is also important that the neutral bus is protected against overvoltages delivered to the station from the line and conducted through the filters to the low voltage neutral bus. An arrester, possibly in parallel with a surge capacitor (as shown in Figure 33), therefore, is often used for overvoltage protection of the neutral bus.

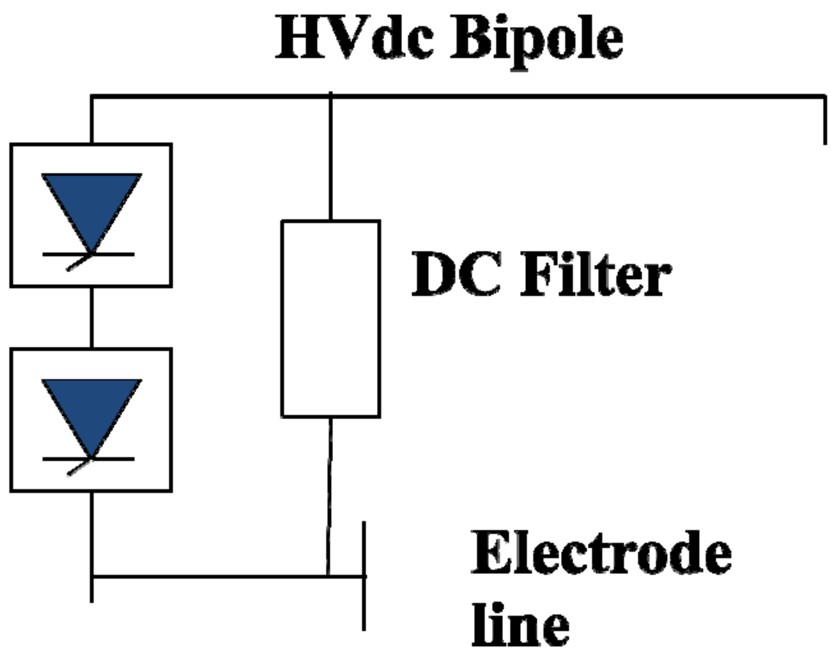

Figure 32. Simplified DC side filter arrangement.

Non-characteristic harmonics injected into the DC line will also arise for a number of additional reasons. Some of these include:

- The AC system feeding the converters is unbalanced.
- The transformer impedances are not exactly equal for each phase and group.
- The firing of the converter valves is not precisely equally spaced.

Some of the harmonics generated inside the converters can be injected into the electrode line. Odd harmonics such as the 3rd, 9th, etc. are so called "triplen harmonics" and are generated through the stray capacitances from the transformers (Figure 33) (Larsen et al., 1989). Since the neutral in the transformer blocks triplen harmonics (isolated from ground), a large 3rd harmonic voltage between the converter transformer's neutral point and ground results. Since these harmonic voltages cause a current flow through stray capacitances to ground, the current must return through the electrode line or a low impedance path for harmonic currents connected between the neutral bus and the station ground grid. This is one reason for non-characteristic harmonic current flows on electrode lines.[8] Although small, such harmonic current flows might cause telephone interference depending on the magnitude of harmonic currents and the proximity and parallel length of telephone lines. Since the 3rd harmonic at 180 Hz is below the lower threshold of a telephone channel at 300 Hz and the 9th harmonic at 540 Hz is towards the lower end of the typical 4 kHz bandwidth for a voice grade channel, the interference factor is probably below the threshold where it will be noticeable by telephone users unless the electrode line happens to be tuned to one of the non-characteristic harmonics[9]. One factor to consider is that these harmonic currents are not related to the DC line current but arise as a result of the commutation voltages in the converter groups. That is, they could have a higher magnitude at low operating power levels than at high operating power levels.

Figure 33. Stray capacitance from the transformers to ground.

Commutation voltage transients will also cause current flow through stray capacitances from valves, bushings, and bus structures to ground. If there are high frequency blocking filters inserted between the lower voltage converter group and the neutral bus, these transients should not propagate along the electrode line. If not, there is the possibility for interference with

8 If the smoothing reactor is placed at the neutral end of the converter groups, then the triplen harmonics will enter the DC pole conductor instead of the electrode line.

9 The electrode line at the Celilo converter station of the Pacific Intertie transmission line was tuned to the 6th harmonic, which caused some telephone interference.

systems operating in the kHz to hundreds of kHz range. That is, there is a possibility for radio and carrier communication system interference as a result of conducted transients injected into the electrode line even if the line does not have corona discharges.

Electric and magnetic fields from the electrode line

As can be seen in Figure 34, the DC filter creates a path for transients to enter the neutral bus when connected to this bus. If the filter is connected to the station ground, then the harmonics generated in the converter groups will have to go through the electrode line in order to return to their source in the converters unless there is a low impedance path for the harmonics from the station ground mat to the neutral bus. A capacitor connected from the neutral bus to ground can serve as a low impedance path for harmonics. (Such a capacitor will also allow triplen harmonics discussed above to return to the converter where they were generated.)

The electrode line can also conduct lightning surges into the station, requiring a surge arrester connected between the neutral bus and station ground as shown in Figure 34. This limits the electric fields at the point at which the arrester is connected to the neutral bus to the protection level of the arrester. That is, the voltage at the station end of the electrode line will be at or below the voltage at which the arrester conducts current.

Lightning striking the electrode line will cause line overvoltage, potentially to the point causing a flashover (an arc) across a line insulator. Such faults are difficult to detect and are also difficult to isolate to allow the line insulation to recover. In at least one monopole DC line project a sufficient number of insulators were installed for the electrode line to enable the DC current flow through the fault to extinguish by itself. In a bipolar system such as the Bipole III line, the current in the electrode line will normally be very low and a fault current from the electrode line to ground would most likely extinguish by itself. If the electrode is carrying 2,750 A, however, the arc voltage generated at the fault location from the magnetic forces that cause the arc to become elongated might not be sufficient to extinguish the arc unless the air gap is large.[10] The air gap or the required insulator length would most likely have to be longer closer to the

[10] The emergency rating of the electrode line should be used when selecting the appropriate number of insulators to use for the line.

converter station as opposed to closer to the electrode site to accomplish natural commutation of the fault current back into the electrode line conductor.

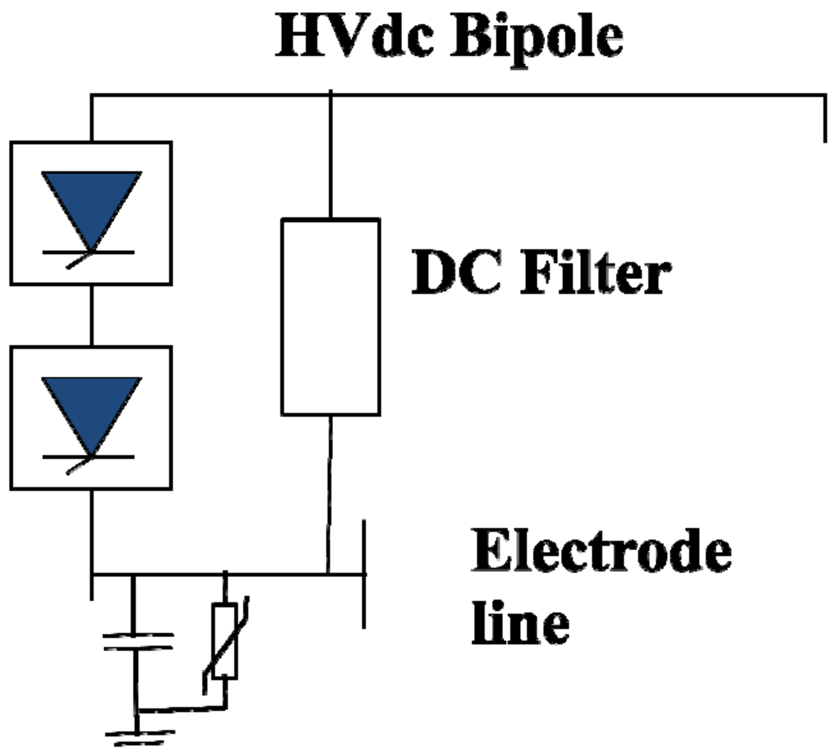

Figure 34. Common neutral bus overvoltage protection and bus capacitor.

6. Converter Station

Converter stations will be connected to each end of the Bipole III line to transfer AC to DC power at the northern converter and DC to AC power at the southern converter. In addition there will be associated equipment and facilities to connect to AC transmission lines and switching facilities.

The electric and magnetic fields associated with equipment in the converter station would not be expected to cause field levels outside the boundaries of the large proposed sites to be significantly elevated except where power lines, e.g., Bipole III, or connections to the AC grid traverse the boundary. The field levels associated with the operation of Bipole III have been characterized above in Section 3.

As discussed in Section 4, however, the output voltage from the converter will mainly contain 12-pulse harmonics and multiples thereof and can be a potential source of conducted as well as radiated interference at frequencies above the telephone interference spectrum. The commutation of the valve currents from one valve to the adjacent valve is associated with short duration short circuits between the AC phase voltages. These switching transients also cause charging and discharging currents to flow through stray capacitances from the equipment to ground or between equipment connected to difference phases. The commutation leads to one transient voltage change when a valve is turned on and another when the valve is turned off. Thus, in a 6-pulse group connected to a 60-Hz system, there will be two sets of transients with a 360-Hz repetition frequency.

The RN levels from thyristor switched valves depend on a number of factors. The turn-on speed of the thyristors is one of these factors (Temple, 1981). A slower turn-on speed tends to reduce the higher frequencies in the RN spectrum but at the expense of higher switching losses. The valve halls are typically built as shielded rooms to prevent significant RN from the valve switching. Some relatively low-level high-frequency currents, however, may escape the building via the converter transformers and DC bus connections to the smoothing reactors and the electrode line (EPRI, 1986). Although the impedance of a transformer might be viewed as an inductance for power system frequencies, the high frequency impedance of a transformer is complex and appears as a series capacitance or as a series resonant circuit with hardly any attenuation for some frequencies. Similarly, a capacitor might be represented by an inductance at some higher frequencies. Therefore, special RF blocking filters are sometimes installed in the AC and DC busses in the valve hall to reduce the RF noise levels outside the converter station.

The switching-related current impulses injected into the busses leaving the valve hall causes RF energy to be radiated from the AC and DC busses, but the impulse currents can also cause interference with carrier communication systems (Hylten-Cavallius et al., 1964; Annestrand, 1972; Patterson, 1985; Maruvada et al., 1989; EPRI, 1994) . The interference levels are typically worse for AM communication systems. Thus, in addition to carrier communications system interference, long wave through short wave AM radio systems can be affected. Thus, most of the RN frequencies of concern are below 1 megahertz (MHz). FM systems are typically not affected by the valve switching.

Assuming standard design practices to minimize RF interference from the converter station and electrode line, harmonics and RF are not likely to be a problem, and if interference is detected, it will be mitigated.

7. Assessment Criteria and Conclusions

DC fields and ions

For DC electric and magnetic fields, two organizations have developed guidance. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) recently published guidelines on exposure to DC magnetic fields that included a limit for exposure of the general public of 400 millitesla (mT), which is equivalent to 4,000,000 mG (ICNIRP, 2009). The magnetic field contributed by the line in normal operation to the background geomagnetic field is a very, very small fraction of this limit; on the ROW the magnetic field contributed by the line is less than 360 mG. Higher magnetic fields will occur during some infrequent emergency ground return operating modes.

The National Radiological Protection Board of Great Britain (NRPB), now a division within the Health Protection Agency of Great Britain, has recommended 25 kV/m as the limit on the exposure of the general public to DC electric fields (NRPB, 1994). A similar value has been recommended as a threshold limit value for occupational exposures (ACGIH, 2009). A higher value of 42 kV/m was recommended as an upper limit (basic restriction) in a Comité Européen de Normalisation Électrotechnique pre-standard (CENELEC, 1995). In fair weather, the calculated DC electric fields of Bipole III are below 25 kV/m. In foul weather, in which persons are less likely to be on the ROW, the DC electric fields are expected to exceed this value within the ROW for about 10 m on either side of Bipole III for no-wind conditions.

No scientific or regulatory agency has determined that small air ions, a measure of air ions and electric fields together (ion current density) pose a threat to the environment or health, so no exposure guidelines have been proposed. Small air ions are found at varying levels in the everyday environment. Since *low* levels of air ions in buildings have been alleged as symptomatic of poor indoor air quality, the Ministry of Health of the Russian Federation has recommended that (+) and (-) air ion levels be maintained between a minimum level of 400 ions/cm^3 and a maximum level of 50,000 ions/cm^3 for public and industrial quarters (MHRF, 2003). The basis for the guideline was not described in this hygienic norm. The levels of air ions on the ROW exceed this range but fall well within this range outside the ROW and are similar to those found in environments not near a DC transmission line.

DC audible noise

Manitoba's Provincial Guidelines specify maximum desirable 1-hour equivalent noise levels for residential and commercial areas of 55 d-BA and 45 d-BA, for day-time and night-time periods, respectively (EMD, 1992). These standards will be met by Bipole III in fair weather even under the conductors on the ROW. In foul weather, the levels of AN will be even lower and typically masked by noise from wind and rain.

DC radio noise

The Industry Canada standard for RN for a 500-kV transmission line is 60 dBμV/m at 15 m from the nearest conductor that would be measured by a CISPR-type measuring instrument according to CSA Standard C108.1.1-1977 (Industry Canada, 2001). This standard will be met by Bipole III at the edges of the ROW and beyond in fair weather; in foul weather the levels will be even lower.

Ground electrode/electrode line

In normal operation the ground electrode and electrode line will be associated with very weak electric and magnetic fields. During monopolar operation with ground return the magnetic field and electric fields will increase but still will be far below recommended limits discussed above. The voltages on the electrode line will be too low to be a cause of corona-related AN or RN.

The ground electrode is designed to operate at a continuous current of 2,000 A and a higher current of 2,500 A for a more limited period of time. Step potentials have been estimated to be less than 10 V/m at 2,250 A and thus should not pose a hazard to humans and animals on the site or to fish in a stream 800 m distant.

There will be no effects on the operation of communication equipment or radio/TV reception due to the low operating voltage of the electrode line and the electrode. The physical presence of the conductors and tower structures may cause scattering, reflection, or reradiation of primary TV broadcast signals. TV and RN interference may result from gap sparking caused by faulty or loose fittings; such situations are easily remedied by routine maintenance. Although harmonic voltages and currents on the electrode line can sometimes be a source of interference to telephone communication, it can be mitigated.

Conclusions

Based on the modeling of the DC Bipole III transmission line and the ground electrode lines, the following conclusions were drawn:

- The small differences in conductor size and spacing between the guyed and self-supporting Bipole III tower structures result in negligible differences in the levels of calculated electric parameters.

- In general, the calculated peak levels of AN and RN under Bipole III are substantially lower than under Bipoles I and II and the levels of electric field, air ions, and ion currents are similar. Only the peak magnetic field under the Bipole III line is higher and this is because it was modeled at higher loading than Bipoles I and II. Bipole III was designed to operate at the same loading as Bipole II.

- During rare periods of monopolar operation, the levels of DC electric fields, air ions, and ion current density will increase slightly (~10%) on the ROW and the edge of the ROW closest to the operating pole compared to bipolar operation; levels are decreased by a larger percentage at the edge of the ROW closest to the inactive pole. In contrast, AN and RN levels decrease across the ROW, particularly during monopolar negative pole operation.

- At ground electrode sites, the levels of DC electric and magnetic fields will be very low but will increase substantially above the buried electrode and beneath the electrode lines during some rare emergency monopolar operations. The electrode is designed to keep the step potentials low during monopolar operation so as to prevent shocks to persons or animals on the site and beyond. AC harmonics on the electrode line and RF noise from the converter station are a possible source of interference to telephone communication and AM radio reception but can be mitigated.

- The levels of magnetic fields, electric fields, AN, RN, and small air ions outside the ROW of Bipole III are all below limits recommended by provincial, national, and international agencies. No guidance for the ion current density was identified but compliance of Bipole III with both electric field and small air ion recommended limits indicates that this parameter, computed as the product of the electric field and small ion concentration, is not of additional consequence.

- A comparison between Bipole III and six other DC transmission lines in North America shows that the median peak levels of DC electric field and small air ions of Bipole III are lower than the levels of five other DC transmission lines.

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Appendix A

Input data for EMF, AN, and RN modeling of Bipole III DC Transmission Line

Table A-1. Bipole conductor types

Tower Type	Voltage [kV]	Conductor type	Conductor diameter [mm]	Number of conductors	Conductor spacing [mm]	SW type	SW diameter [mm]
Bipole III Guyed Tower	500	806-A4-61 (Al Alloy)	38.01	3	457	OPGW	13.4
Bipole III Self-supporting Tower	500	806-A4-61 (Al Alloy)	38.01	3	457	OPGW	17.5
Bipole I & II	463 / 500	1843.2ACSR	40.6	2	457	3/8EHS	9.1

Table A-2. Bipole loading and conductor locations

Tower Type	Loading (MW)	Conductor height at mid-span (m)[4] (-) X	(-) Y	(+) X	(+) Y	Shield wire height at mid-span (m)[4] X	Y	ROW width (m)
Bipole III Guyed Tower	2000[1]	-7.5	13.2	+7.5	13.2	0	27.9	±33
	2500[2, 5]	-7.5	13.0	+7.5	13.0	0	27.9	
	4000[3, 6]	-7.5	11.8	+7.5	11.8	0	27.9	
Bipole III Self-supporting Tower	2000[1]	-7.75	13.2	+7.75	13.2	0	27.9	±33
	2500[2, 5]	-7.75	13.0	+7.75	13.0	0	27.9	
	4000[3, 6]	-7.75	11.8	+7.75	11.8	0	27.9	
Bipole I Guyed Towers	1559/line[1]	-39.2	13.5	25.8	13.5	-32.5[7]	25.8	±55
Bipole II	1681/line[1]	-25.8	13.5	39.2	13.5	32.5[8]	25.8	

[1]Typical loading

[2]Contingencyloading

[3]Emergency loading – once per 10-15 years

[4]Sag based on ambient temperature (summer) - 40°C; Wind - 0.6 m/s); Wind direction - perpendicular to conductor; Conductor orientation - North-South; Coefficient of emissivity - 0.5, Coefficient of solar absorptivity - 0.5

[5] Conductor summer operating temperature 65°C

[6] Conductor summer operating temperature 90°C

[7] Shield wire for western/northern tower

[8] Shield wire for eastern/southern tower

Appendix B

Modeling results: positive pole, monopolar operation

Table B-1. Electric Fields (kV/m) – Bipole III Guyed Tower, Operating Monopolar Positive

Guyed Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Fair (kV/m)	2.6	25.5	7
	Foul (kV/m)	3.9	34.1	10.1
Contingency Load	Fair (kV/m)	2.6	26.0	7.0
	Foul (kV/m)	3.9	34.7	10.1
Emergency Load	Fair (kV/m)	2.6	29.3	6.9
	Foul (kV/m)	3.9	38.8	10.1

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table B-2 Electric Fields (kV/m) – Bipole III Self-supporting Lattice Tower, Operating Monopolar Positive

Self-supporting Lattice Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Fair (kV/m)	2.5	25.5	7.1
	Foul (kV/m)	3.9	34.1	10.3
Contingency Load	Fair (kV/m)	2.6	26.0	7.1
	Foul (kV/m)	3.9	34.7	10.2
Emergency Load	Fair (kV/m)	2.6	29.3	7.0
	Foul (kV/m)	3.9	38.9	10.2

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table B-3. Magnetic Fields (mG) – Bipole III Guyed Tower, Operating Monopolar Positive

Guyed Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Total (mG)	49.8	280.2	49.8
Contingency Load	Total (mG)	62.5	358.9	62.5
Emergency Load	Total (mG)	102.7	666.7	102.7

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table B-4. Magnetic Fields (mG) – BIPOLE III Self-supporting Lattice Tower Operating Monopolar Positive

Self-supporting Lattice Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Total (mG)	51.5	284.0	51.5
Contingency Load	Total (mG)	64.7	363.6	64.7
Emergency Load	Total (mG)	106.4	673.7	106.4

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table B-5. Ion Current Flux (nA/m^2) – BIPOLE III Guyed Tower, Operating Monopolar Positive

Guyed Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Fair (nA/m^2)	0	58	2
	Foul (nA/m^2)	0	101	4
Contingency Load	Fair (nA/m^2)	0	61	2
	Foul (nA/m^2)	0	106	4
Emergency Load	Fair (nA/m^2)	0	83	2
	Foul (nA/m^2)	0	143	4

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table B-6. Ion Current Flux (nA/m^2) – BIPOLE III Self-supporting Lattice Tower, Operating Monopolar Positive

Self-supporting Lattice Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Fair (nA/m^2)	0	58	3
	Foul (nA/m^2)	0	101	5
Contingency Load	Fair (nA/m^2)	0	61	3
	Foul (nA/m^2)	0	106	4
Emergency Load	Fair (nA/m^2)	0	83	3
	Foul (nA/m^2)	0	144	4

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table B-7. Ion Density ($ions/cm^3$) – BIPOLE III Guyed Tower, Operating Monopolar Positive

Guyed Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Fair ($ions/cm^3$)	5,100	123,400	19,150
	Foul ($ions/cm^3$)	5,900	160,650	23,050
Contingency Load	Fair ($ions/cm^3$)	5,150	127,200	19,350
	Foul ($ions/cm^3$)	5,900	165,600	23,250
Emergency Load	Fair ($ions/ cm^3$)	5,300	154,300	19,600
	Foul ($ions/cm^3$)	6,050	200,850	23,400

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table B-8. Ion Density ($ions/cm^3$) – BIPOLE III Self-supporting Lattice Tower, Operating Monopolar Positive

Self-supporting Lattice Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Fair ($ions/ cm^3$)	5,050	123,200	19,750
	Foul ($ions/cm^3$)	5,850	160,600	23,800
Contingency Load	Fair ($ions/cm^3$)	5,100	127,050	19,600
	Foul ($ions/cm^3$)	5,850	165,550	23,600
Emergency Load	Fair ($ions/cm^3$)	5,250	154,250	19,900
	Foul ($ions/cm^3$)	6,000	200,850	23,800

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table B-9. Audible Noise (dB-A) – BIPOLE III Guyed Tower, Operating Monopolar Positive (275m Altitude)

Guyed Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Fair (dB-A)	26.9	31.2	28.6
	Foul (dB-A)	20.9	25.2	22.6
Contingency Load	Fair (dB-A)	26.9	31.3	28.7
	Foul (dB-A)	20.9	25.3	22.7
Emergency Load	Fair (dB-A)	27.2	31.7	29.0
	Foul (dB-A)	21.2	25.7	23.0

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table B-10. Audible Noise (dB-A) – BIPOLE III Self-supporting Lattice Tower, Operating Monopolar Positive (275m Altitude)

Self-supporting Lattice Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Fair (dB-A)	26.6	31.0	28.5
	Foul (dB-A)	20.6	25.0	22.5
Contingency Load	Fair (dB-A)	26.7	31.0	28.5
	Foul (dB-A)	20.7	25.0	22.5
Emergency Load	Fair (dB-A)	26.9	31.5	28.8
	Foul (dB-A)	20.9	25.5	22.8

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table B-11. Radio Noise (dB-μV/m) – BIPOLE III Guyed Tower, Operating Monopolar Positive (275m Altitude)

Guyed Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Fair (dB-μV/m)	41.4	59.7	45.8
	Foul (dB-μV/m)	35.4	53.7	39.8
Contingency Load	Fair (dB-μV/m)	41.3	59.9	45.7
	Foul (dB-μV/m)	35.3	53.9	39.7
Emergency Load	Fair (dB-μV/m)	40.7	60.9	45.2
	Foul (dB-μV/m)	34.7	54.9	39.2

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table B-12. Radio Noise (dB-μV/m) – BIPOLE III Self-supporting Lattice Tower, Operating Monopolar Positive (275m Altitude)

Self-supporting Lattice Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Fair (dB-μV/m)	41.4	59.7	45.9
	Foul (dB-μV/m)	35.4	53.7	39.9
Contingency Load	Fair (dB-μV/m)	41.3	59.8	45.8
	Foul (dB-μV/m)	35.3	53.8	39.8
Emergency Load	Fair (dB-μV/m)	40.7	60.8	45.2
	Foul (dB-μV/m)	34.7	54.8	39.2

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Appendix C

Modeling results: negative pole, monopolar operation

Table C-1. Electric Fields (kV/m) – BIPOLE III Guyed Tower, Operating Monopolar Negative

Guyed Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Fair (kV/m)	-4.7	-19.1	-1.6
	Foul (kV/m)	-10.1	-34.1	-3.9
Contingency Load	Fair (kV/m)	-4.7	-19.5	-1.6
	Foul (kV/m)	-10.1	-34.7	-3.9
Emergency Load	Fair (kV/m)	-4.6	-22.1	-1.6
	Foul (kV/m)	-10.1	-38.8	-3.8

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table C-2. Electric Fields (kV/m) – BIPOLE III Self-supporting Lattice Tower, Operating Monopolar Negative

Self-supporting Lattice Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Fair (kV/m)	-4.7	-19.1	-1.6
	Foul (kV/m)	-10.3	-34.1	-3.9
Contingency Load	Fair (kV/m)	-4.7	-19.5	-1.6
	Foul (kV/m)	-10.2	-34.7	-3.9
Emergency Load	Fair (kV/m)	-4.7	-22.2	-1.6
	Foul (kV/m)	-10.2	-38.9	-3.9

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table C-3. Magnetic Fields (mG) – BIPOLE III Guyed Tower, Operating Monopolar Negative

Guyed Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Total (mG)	49.8	280.2	49.8
Contingency Load	Total (mG)	62.5	358.9	62.5
Emergency Load	Total (mG)	102.7	666.7	102.7

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table C-4. Magnetic Fields (mG) – BIPOLE III Self-supporting Lattice Tower, Operating Monopolar Negative

Self-supporting Lattice Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Total (mG)	51.5	284.0	51.5
Contingency Load	Total (mG)	64.7	363.6	64.7
Emergency Load	Total (mG)	106.4	673.7	106.4

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table C-5. Ion Current Flux (nA/m^2) – BIPOLE III Guyed Tower, Operating Monopolar Negative

Guyed Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Fair (nA/m^2)	-1	-34	0
	Foul (nA/m^2)	-6	-131	-1
Contingency Load	Fair (nA/m^2)	-1	-36	0
	Foul (nA/m^2)	-6	-138	-1
Emergency Load	Fair (nA/m^2)	-1	-50	0
	Foul (nA/m^2)	-6	-187	-1

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table C-6. Ion Current Flux (nA/m^2) – BIPOLE III Self-supporting Lattice Tower, Operating Monopolar Negative

Self-supporting Lattice Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Fair (nA/m^2)	-1	-34	0
	Foul (nA/m^2)	-6	-131	-1
Contingency Load	Fair (nA/m^2)	-1	-36	0
	Foul (nA/m^2)	-6	-138	-1
Emergency Load	Fair (nA/m^2)	-2	-50	0
	Foul (nA/m^2)	-6	-188	-1

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table C-7. Ion Density ($ions/cm^3$) – BIPOLE III Guyed Tower, Operating Monopolar Negative

Guyed Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Fair ($ions/cm^3$)	-12,800	-73,800	-3,700
	Foul ($ions/cm^3$)	-22,250	-165,650	-5,900
Contingency Load	Fair ($ions/cm^3$)	-13,000	-76,250	-3,750
	Foul ($ions/cm^3$)	--23,250	-165,600	-5,900
Emergency Load	Fair ($ions/cm^3$)	-13,500	-93,550	-3,900
	Foul ($ions/cm^3$)	-23,400	-200,850	-6,050

*Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table C-8. Ion Density ($ions/cm^3$) – BIPOLE III Self-supporting Lattice Tower, Operating Monopolar Negative

Self-supporting Lattice Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Fair ($ions/cm^3$)	-13,250	-73,550	-3,650
	Foul ($ions/cm^3$)	-23,800	-160,600	-5,850
Contingency Load	Fair ($ions/cm^3$)	-13,150	-76,000	-3,700
	Foul ($ions/cm^3$)	-23,600	-165,550	-5,850
Emergency Load	Fair ($ions/cm^3$)	-13,650	-93,350	-3,900
	Foul ($ions/cm^3$)	-23,800	-200,850	-6,000

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table C-9. Audible Noise (dB-A) – BIPOLE III Guyed Tower, Operating Monopolar Negative (275m Altitude)

Guyed Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Fair (dB-A)	4.5	6.4	4.5
	Foul (dB-A)	<1	<1	<1
Contingency Load	Fair (dB-A)	4.2	6.0	4.2
	Foul (dB-A)	<1	<1	<1
Emergency Load	Fair (dB-A)	1.9	3.8	1.9
	Foul (dB-A)	<1	<1	<1

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table C-10. Audible Noise (dB-A) – BIPOLE III Self-supporting Lattice Tower, Operating Monopolar Negative (275m Altitude)

Self-supporting Lattice Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Fair (dB-A)	<1	<1	<1
	Foul (dB-A)	<1	<1	<1
Contingency Load	Fair (dB-A)	<1	<1	<1
	Foul (dB-A)	<1	<1	<1
Emergency Load	Fair (dB-A)	<1	<1	<1
	Foul (dB-A)	<1	<1	<1

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table C-11. Radio Noise (dB-μV/m) – BIPOLE III Guyed Tower, Operating Monopolar Negative (275m Altitude)

Guyed Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Fair (dB-μV/m)	<1	<1	<1
	Foul (dB-μV/m)	<1	<1	<1
Contingency Load	Fair (dB-μV/m)	<1	<1	<1
	Foul (dB-μV/m)	<1	<1	<1
Emergency Load	Fair (dB-μV/m)	<1	<1	<1
	Foul (dB-μV/m)	<1	<1	<1

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Table C-12. Radio Noise (dB-µV/m) – BIPOLE III Self-supporting Lattice Tower, Operating Monopolar Negative (275m Altitude)

Self-supporting Lattice Tower Load Conditions*		ROW Edge (-33m)	Profile Peak (within ROW)	ROW Edge (33m)
Typical Load	Fair (dB-µV/m)	<1	<1	<1
	Foul (dB-µV/m)	<1	<1	<1
Contingency Load	Fair (dB-µV/m)	<1	<1	<1
	Foul (dB-µV/m)	<1	<1	<1
Emergency Load	Fair (dB-µV/m)	<1	<1	<1
	Foul (dB-µV/m)	<1	<1	<1

* Typical load = 2,000 MW; contingency load = 2,500 MW; emergency load = 4,000 MW

Appendix 2

Space charge and research on the respiratory system, mood, and behavior

Space charge and research on the respiratory system, mood, and behavior

Collectively small air ions and charged aerosols are referred to as space charge. Air ions are simply air molecules that have gained or lost electrical charges, so it is understandable that investigations into their effects would focus on the respiratory system and the skin. The interactions of air ions with the body are similar to interactions with other components of the air (e.g., gases such as oxygen and nitrogen), except that charged particles can be attracted to and deposited on the skin and respiratory tract by electrostatic forces. The deposition of particles on the skin is the same as produced by wind (NRPB, 2004a). Consideration of such forces with respect to the respiratory tract suggests that most of the air ions would be retained in the nose and bronchi with few reaching the deep alveoli of the lung (MEQB, 1982). Despite many theories offered over the years, however, no mechanism has been confirmed to explain how air ions could exert any significant biological effect on respiratory or other systems (MEQB, 1982; NRPB, 2004a).

One mechanism by which air ions are neutralized is the transfer of charge from small air ions to larger aerosols (charged aerosols). This route of interaction of space charge with the body has been given less attention because ambient aerosols are already charged to some degree, and for particles up to 1 µm, multiple charges up to 5 or 10 Q (Q = the charge on a single electron) are quite likely (Kunkel, 1950).

Laboratory studies have demonstrated that large amounts of charge on aerosol particles increase their deposition in the respiratory tract. Melandri et al. (1977, 1983) were able to determine the level of charge per particle that had to be exceeded to increase deposition in the human respiratory tract above that of uncharged particles. This particle charge threshold was as low as Q = 9 for 0.3 µm diameter particles and as high as Q = 21-49 for 0.6 µm and 1.0 µm particles. (Common atmospheric aerosols, such as dust and pollen, are generally composed of particles 1.0 µm or larger in diameter, while the particles of fumes and smoke generally have diameters less than 1.0 µm).

This work has been confirmed by Prodi and Mularoni (1985) who reported that 29 Q was required to enhance deposition of 0.6 µm particles. Scheuch et al. (1990) reported that conditions simulating the operation of a room ionizer in a closed room achieved about 50 charges per particle (50 Q) but increased deposition of particles in the human respiratory tract by less than 2% (0.5 µm particles) or 6.4% (1.4 µm particles).

Hoppel (1980) has calculated an upper bound for the median charge on particles of different sizes as a function of particle concentration and charging time for particles carried downwind of a DC transmission line. His results suggest that few aerosol particles less than 1.0 µm in diameter would acquire a charge greater than 10 Q per particle. This is within the range of a Maxwell-Boltzman distribution that describes the distribution of charge on aerosols under equilibrium conditions (NRPB, 2004a), and thus does not indicate that a DC transmission line would add sufficient charge to aerosols beyond that already present to significantly enhance deposition.

A review of research on the DC transmission line environment by MEQB with respect to the dosimetry of charged aerosols concluded it is unlikely that particles can be charged to a sufficient degree or be present in high enough concentrations for this to be a problem (MEQB, 1982). Speculation as to whether exposure to ambient aerosols is increased by the addition of electrical charge from corona on AC transmission lines has been raised on theoretical grounds, but no supporting experimental evidence in humans has been put forth to support this specific claim (Fews et al., 1999, 2002). Assessments of this hypothesis have criticized it on multiple grounds (NRPB 2004a; Jeffers, 2005; WHO, 2007), including a lack of established relevance to health (IARC, 2002). More recent modeling of aerosol charging by a DC transmission line has confirmed that it could not add enough additional charges to aerosols to cause enhanced deposition in the respiratory tract (Jeffers, 2007). This modeling is consistent with that of Hoppel (1980) and with the measurements of charges on aerosols near DC transmission lines. The above conclusions are supported by the measurements of charged aerosols around the existing Bipole I and II DC transmission lines that suggested no increase in the fraction of aerosols charged or the number of charges per particle (Bailey et al., (2011).

Since the discovery of electrical charges on molecules in the air (Elster and Geitel, 1899), there has been speculation about their influence on biological processes. A considerable amount of popular and scientific literature has evolved since then; animals, humans, and lower organisms (microorganisms, plants) have been studied to look for potential effects of space charge in the form of small air ions and larger charged aerosols. Laboratory studies of humans and animals have evaluated a wide range of exposures from ambient levels (about 1,000 ions/cm^3), to levels in the range of those found directly under a DC transmission line (i.e., about 100,000 ions/cm^3), and to very much higher levels (2,000,000 ions/cm^3).

The effects of artificially generated air ions on humans have been studied for both experimental and therapeutic purposes. In addition, attempts have been made to investigate naturally occurring variations in air ion levels in relation to a variety of physiological conditions. The reported biological and behavioral responses to air ion exposures in these studies, however, are often inconsistent. Positive and negative air ion exposures sometimes have been reported to exert opposite effects, while many other studies reported no effects.

The large quantity of studies that have been conducted to evaluate potential biological and therapeutic effects of space charge provide a basis to evaluate the relevance of expected space charge from the proposed Bipole III transmission line to human and animal health. Most of this research has been thoroughly evaluated by the panel of scientists assembled by the MEQB (MEQB, 1982). Their overall conclusion regarding air ions was:

> In summary, while air ions appear to affect some biological processes in animals, plants, and microorganisms, there is insufficient reason to believe that acute exposures to air ions are harmful or injurious. As far as is known, all effects that have been described in animals and humans are quite mild and fully reversible, usually within a few hours. However, there are insufficient data to determine what effects, if any, might be observed with exposures to high ion concentrations over extended periods of time (MEQB, 1982, pp. 8-9).

Similar conclusions are reached in later reviews (MEQB, 1986; Bailey, 1987; Charry, 1987). Human studies are most relevant to the assessment of potential effects in humans, and they are inherently less susceptible to artifacts than some types of animal studies (because of behavioral and biological responses to sensory stimulation of body hair by space charge and the electric field when present at high concentrations).[1]

This assessment focuses on two areas of research on human subjects with relevance to the DC transmission line environment: 1) potential effects of space charge on the respiratory system because it appears to be the only route of exposure for air ions with any potential health relevance; and 2) research on the effects of air ions on mood. These areas of research are summarized below, following a discussion of a single study of the Pacific Intertie DC transmission line that evaluated multiple outcomes.

Study of the Pacific Intertie DC transmission line

A study sponsored by the Vermont Department of Public Service was designed to assess the potential effects of air ions and charged aerosols on people's respiratory and mood indicators. The health experience of a population living near a DC transmission line was compared with a similar population living away from the line. This cross-sectional study focused on a densely populated community through which the Pacific Intertie DC transmission line passes (Nolfi and Haupt, 1982). The Pacific Intertie was first energized in 1970 and runs from Washington State to the Los Angeles area. It had been operating at ±400 kV for almost 12 years at the time the study was conducted (1981), and was upgraded to ±500 kV in 1984. The health endpoints surveyed among the residents included headaches, number of illness days, depression, drowsiness, and respiratory congestion.

Participants in the study were divided into groups depending on how close they lived to the DC transmission line corridor. The "near" group lived within 0.14 miles (225 m) of the corridor and was subdivided into those people who lived on the edge of the corridor and those who lived beyond it. The "far" group lived between 0.65 and 0.85 miles from the line (1 to 1.4 km). Interviews were conducted by home visits, and all members in the household over the age of two were included. Data were collected on 438 individuals from 128 households. The responses from all the groups were compared, and no differences for any of the endpoint measures were

[1] By and large the weight of evidence from animal studies does not indicate any adverse effects of exposure to air ions and associated charged aerosols (MEQB, 1982, 1986).

observed, indicating no acute health impacts. Study quality could have been improved by better exposure measurements and a higher response rate. Nevertheless, the study is consistent with the results of experimental and clinical studies reviewed below and by the MEQB (1982).

Human experimental studies of space charge

The following section evaluates experimental studies of humans exposed to air ions and charged aerosols. These studies evaluated the effect of exposure on the respiratory system, behavior, and mood.

Respiratory system

A systematic literature review was conducted to identify studies relevant to the effects of air ions and space charge on respiratory effects. The MEQB prepared a detailed review of studies relevant to this topic in 1982 (MEQB, 1982). The systematic literature review identified 22 studies including those previously reviewed by the MEQB (1982) and those published thereafter (Table 1).[2] The table describes the measured ion concentration, exposure duration, study measures affected or not affected, and comments regarding strengths and weaknesses of each study.

Air ion exposure levels from 1,600 ions/cm^3 to 1,500,000 ions/cm^3 were measured in 19 of these studies. A wide range of respiratory measures were studied, including respiratory rate, multiple measures of pulmonary function, and respiratory symptoms. Of note, most of the studies were performed to test for a therapeutic effect of air ions. Many of the subjects were adults and children with pre-existing asthma and related respiratory conditions. These studies provide no persuasive evidence for an effect of air ions (and concomitant charged aerosols) on respiratory effects. There was no consistency as to the direction of the response (i.e., beneficial or adverse) or the polarity of ions to which the subjects were exposed (i.e., + or -). Furthermore, there was no clear dose-response relationship. These conclusions are consistent with the MEQB review,

[2] Yaglou et al., 1933; Herrington, 1935; Kornblueh and Griffin, 1955; Kornblueh et al., 1958; Winsor and Beckett, 1958; Zylberberg and Loveless, 1960; Yaglou, 1961; Lefcoe, 1963; Blumstein et al., 1964, Motley and Yanda, 1966; Palti et al., 1966, McDonald et al., 1967; Jones et al., 1976; Albrechtsen et al., 1978; Ben-Dov et al., 1983; Dantzler et al., 1983; Nogrady and Furglass, 1983; Wagner et al., 1983; Kirkham et al., 1984; Lipin et al., 1984; Finnegan et al., 1987; Reilly and Stevenson, 1993.

which stated that only minor symptoms, e.g., throat dryness, were related to experimental ion exposures, with limited evidence of any dose-response relationships. The MEQB also concluded that short- and long-term exposures to positive and negative ions do not affect persons with pre-existing allergies, asthma, or respiratory disease, or persons more sensitive to respiratory irritants. This assessment is also consistent with a recent review by Blackhall et al. (2010) which concluded that research has failed to demonstrate any benefit of air ionizers in the treatment of chronic asthma in children and adults.

These studies had several limitations. Many of the studies did not report blinding the subjects or investigators to exposure to prevent expectation or placebo effects. Some studies did not quantitatively evaluate the respiratory response or measure the level of exposure. Furthermore, none of the studies controlled for the reduction in particulate levels by air ionizers. Therefore, where beneficial effects of air ionizers were reported, it is possible that the benefits resulted from the reduction of particulate levels in the rooms (dust, allergens).

In conclusion, the research does not provide reliable evidence to support the inference that short-term or extended exposure to air ions or charged aerosols (including levels greater than will be produced by the proposed Bipole III project) would produce either adverse or beneficial effects on respiratory function. This is consistent with the conclusion that charges on aerosols are of greater significance for aerosol therapy, in which there may be hundreds to thousands of charges/particle, than for inhalation toxicology (Isaacs et al., 2005).

Behavior and mood

Some of the earliest research on human responses to air ions focused on therapeutic behavioral responses (e.g., Dessauer, 1931; Herrington, 1935; Silverman and Kornblueh, 1957; McGurk, 1959). Changes in air ion concentrations vary with the weather; therefore, some of the impetus for this research was to explain people's subjective responses to weather changes. In addition, the speculation that exposure to negative air ions improves performance and mood was promoted by manufacturers of air ion generators following a widely publicized article in *Reader's Digest* in the 1960s. Some investigators had already formed the impression that exposure to air ions, particularly negative ions, had effects on mood and feelings of well being (Dessauer, 1931; McGurk, 1959), stimulating research that continues to this day.

A systematic literature search was conducted to identify studies relevant to the effects of air ions/charged aerosols on mood and well-being. Thirty English-language studies were identified (Table 2).[3] Table 2 describes the measured ion concentration, exposure duration, study measures affected or not affected, and comments regarding strengths and weaknesses of each study.

All but two (Sigel, 1979, Yaglou, 1961) of the studies were published in peer-reviewed journals. Air ion exposure levels were measured and reported in 23 of these studies and ranged from 1,000 ions/cm^3 to 2,750,000 ions/cm^3. Most studies investigated the potential effects of negative air ions. Seven studies reported no significant response to ion treatment while the remainder reported some type of response. These studies were grouped into four categories which are reviewed separately below.

Observations of Relaxation and Sleepiness

Four studies evaluated relaxation and sleepiness; all reported that positive or negative air ion exposure produced relaxation or sleepiness after exposures lasting between 0.5 and 1.5 hours.[4] These studies had numerous limitations: ion levels were only measured in two studies; the observations were not quantified or systematically evaluated in three studies; the fourth study included only four subjects; and only one study blinded study participants to exposure.

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[3] Silverman and Kornbleuh, 1957; McGurk, 1959; Yaglou, 1961; Assael et al., 1974; Sigel, 1979; Charry and Hawkinshire, 1981; Tom et al., 1981; Buckalew and Rizzuto, 1962; Baron et al., 1985; Dantzler et al., 1983; Deleanu and Stamatiu, 1985; Finnegan et al., 1987; Giannini et al., 1986/1987; Giannini et al., 1986; Hawkins, 1981; Hedge and Collis, 1987; Lips, 1987; Misiaszek et al., 1987; Reilly and Stevenson, 1993; Terman and Terman, 1995; Watanabe et al., 1997; Terman et al., 1998; Nakane et al., 2002; Iwama et al., 2004; Goel et al., 2005; Goel and Etwaroo, 2006; Terman and Terman, 2006; Giannini et al., 2007; Malcolm et al., 2009; Flory et al., 2010.

[4] Silverman and Kornbleuh, 1957; Yaglou, 1961; Assael et al., 1974; Misiaszek et al., 1987.

Personal comfort ratings

Six studies described personal comfort ratings after exposure to positive or negative air ions, ranging from 10 minutes to 6-8 weeks.[5] In three studies, air ions of either polarity had no effect on personal comfort ratings with exposures of 18,000 ions/cm^3, 20,000 ions/cm^3, and 172,000 ions/cm^3. In the remaining three studies, negative ions were reported to increase ratings of improved personal comfort with exposures of 3,500 ions/cm^3, 8,000 ions/cm^3, and 50,000 ions/cm^3. The rating changes in these studies were similar to or less than the small changes associated with environmental exposures (e.g., temperature and humidity). Some precautions were taken to minimize the subjects' awareness of exposure conditions in all six studies.

Ratings of activation, anxiety, and mood

Twelve studies rated the subjects' mood responses to positive or negative air ions at exposure levels between 2,300 ions/cm^3 and 100,000 ions/cm^3 and durations ranging from 15 minutes to 3 days[6]; only one study did not measure air ion levels. Three of the studies reported no response to ion exposures; the remainder reported a variety of responses, which were not consistent in the direction of response to air ions compared to controls or the polarity of ions associated with the response. Where responses were quantified, they were of very small magnitude and weaker than those reported for other environmental factors (e.g., temperature and humidity). Negative ions were more often reported to decrease indicators of tension, anxiety, and a lowered mood rating, but the direction of the response often depended upon characteristics of the subjects and testing conditions.[7] Furthermore, no dose-response relationships were evident. Overall, these studies provide no consistent evidence for the hypothesis that air ions are important modulator of subject responses to environmental conditions.

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5 McGurk, 1959; Hawkins, 1981; Finnegan et al., 1987; Lips, 1987; Reilly and Stevenson, 1993; Watanabe et al., 1997.

6 Sigel, 1979; Charry and Hawkinshire, 1981; Tom et al., 1981; Buckalew and Rizzuto, 1962; Dantzler et al., 1983; Baron et al., 1985; Giannini et al., 1986/1987; Giannini et al., 1986; Hedge and Collis, 1987; Nakane et al., 2002; Iwama et al., 2004; Malcolm et al., 2009.

7 For example, one of the best controlled studies reported that exposure to positive air ions increased ratings of anxiety, inattention, tension, and decreased task involvement on the first day of testing, but the subjects' ratings were the opposite on the second day of testing, i.e., subjects exposed to (+) air ions had lower ratings of anxiety, tension, and higher task involvement (Charry and Hawkinshire, 1981).

Indicators of clinical depression

Eight studies exposed patients with depression to air ions at levels between 3,000 ions/cm^3 and 2,700,000 ions/cm^3 for durations ranging from 1 hour on a single day to 1 hour exposures every day for 30 days.[8] Air ion levels were not measured in five of these studies. Treatment effects were assessed by either standardized assessment ratings by clinicians or patient questionnaires. Seven of these eight studies reported a beneficial effect associated with air ion exposure, the exception being the study by Flory et al. (2010), who reported no response. Some studies provided evidence of a dose-response relationship; five studies reported no clear effect of low air ion levels (~10,000 ions/cm^3), but much higher levels (2,700,000 ions/cm^3) were interpreted as producing a reduction in symptoms of depression. There was also some suggestion that daily exposures for more than 10 to 14 days were required to produce a greater therapeutic response (Terman and Terman, 1995, 2006; Terman et al., 1998; Goel et al., 2005).

While there appears to be some consistency in the positive responses of depressed patients to high levels of air ions, researchers express concern that the effect is an artifact of the placebo or expectation effect. Subject responses to treatments (and the beliefs of the investigators themselves) often can result entirely from the subjects' or investigators' false beliefs that the treatment produces a change. For beneficial effects, this is referred to as a placebo response; conversely, the nocebo response arises from beliefs that an exposure produces harm when it is inert. This problem is compounded when subjects are able to discern whether they have been given a hypothesized effective or ineffective treatment and respond to questions accordingly. For studies of mood and depression where the measure of effect is often subjective, the magnitude of the placebo effect can be considerable.[9] One investigator suggested that the "largest component of antidepressant treatments, including bright light or negative ions, can be the placebo effect" (Flory et al., 2010).

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8 Deleanu and Stamatiu, 1985; Terman and Terman, 1995; Terman et al., 1998; Goel et al., 2005; Goel and Etwaroo, 2006; Terman and Terman, 2006; Giannini et al., 2007; Flory et al., 2010.

9 For example, Burgess et al. (2004) report that exposure to dummy ion generators (inert boxes) each morning for four weeks produced the same reduction in depression ratings as exposure to light in the morning or at night (hypothesized antidepressant treatments).

A number of the studies have failed to report that study participants were blinded to their exposure condition (i.e., single blinding), and an even larger number failed to report that the study investigators were also blinded to exposure assignments (i.e., double blinding). In better studies, such precautions are taken to minimize the potential bias on the part of the subjects and investigators that would affect the study results. This potential bias from the subjects' knowledge and expectations was estimated in some studies by comparing subjects' expectations about treatments with ratings of depression at the conclusion of the study. Some studies reported no association between expectations and outcome, suggesting minimal bias (Terman et al., 1998; Goel and Etwaroo, 2006), while others reported a significant association (Terman and Terman, 2006; Flory et al., 2010), suggesting a greater potential for bias.

Overall, the studies of behavior and mood in subjects exposed to air ions do not show any consistent results with respect to relaxation and sleepiness, personal comfort ratings, and ratings of activation, anxiety, and mood. If there is any influence of air ions on these measures, the effect is less than is observed for small changes in other environmental factors, e.g., humidity and temperature. While a beneficial effect on depression was observed in studies with exposures to high levels of air ions, this is likely due to the placebo effect. Most studies had limitations in their design and procedures. Some limitations may have led to artifactual findings, while other limitations (e.g., small number of subjects and failure to measure ion concentrations) are inadequacies that reduce the investigators' ability to detect an effect, if it exists.

In conclusion, the research to date does not show that air ions at the levels and durations of exposures that might be encountered by persons around the proposed Bipole III transmission line have any adverse effects on behavior and mood.

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Table 2-1. Studies of air ions and respiratory parameters

Study Author(s), Year	Ion Polarity	Ion Concentration (ions/cm^3)	Exposure Duration	Parameters NOT Affected by Ion Exposure	Effects Reported	Design QA
Yaglou et al., 1933	(-)	5.0×10^2 - 1.5×10^6	1 hr (30 min - 3 hrs)	Respiration rate		**Strengths:** Ss blinded **Weaknesses:** No blinded analysis; test subject randomization not reported.
	(+)	1.0×10^4 - 1.25×10^6				
Herrington, 1935	(-) / (+)	5.0-6.0 x 10^6	30 min	Respiratory rate		**Strengths:** Detailed description of procedure **Weaknesses:** Ss not blinded; no blinded analysis; test subject randomization not reported.
Kornblueh and Griffin, 1955	(-)	< 1.0 x 10^4	10-110 min		17/27 patients reported partial or complete reduction in symptoms of allergy and asthma.	**Weaknesses:** Exact ion concentrations not measured or reported; no quantitative measures reported; subjective relief in symptoms assessed; blinded analysis and test subject randomization not reported.
Kornbleuh et al., 1958	(-)	1.2-2.6 x 10^3	12-50 min	37/37 patients without symptoms at time of exposure not affected	34/54 symptomatic patients reported relief of hay fever and asthma symptoms.	**Weaknesses:** No quantitative measures reported; subjective relief in symptoms assessed; Ss not blinded; blinded analysis and test subject randomization not reported.
	(+)	2.0-6.5 x 10^3	12-50 min		4/5 symptomatic patients reported no relief of hay fever and asthma symptoms; 6/10 asymptomatic patients experienced symptoms with exposure.	
Winsor and Beckett, 1958	(-)	3.2 x 10^4	20 min	9/13 subjects: no symptoms	4/13 subjects: slight dryness, irritation of nose and throat.	**Strengths:** Ss blinded, S beds grounded **Weaknesses:** Few quantitative measures reported; subjective reports of symptoms assessed; other experiments assessing duration of symptoms and effects of switching from (+) to (-) ions also conducted; blinded analysis and test subject randomization not reported.
	(+)		20 min		Increase in symptoms in all subjects (headache, nasal obstruction, sore throat, etc). "All symptoms were mild."	
			2 x 15 min		Increase in symptoms in 17/20 subjects	
			10 min		Increased upper airway congestion	

Study Author(s), Year	Ion Polarity	Ion Concentration (ions/cm3)	Exposure Duration	Parameters NOT Affected by Ion Exposure	Effects Reported	Design QA
Zylberberg and Loveless, 1960	(-)	NR	120 min	Symptoms of wheezing or dyspnea		**Strengths:** Double blind, randomized study **Weaknesses:** Subjects exposed to (-) and (+) ions in random order; no control group evaluated.
	(+)	NR	120 min			
Yaglou, 1961	(-)	5.0-10.0 x 10^3	1-2 hrs	Respiration rate; no effect on subjective rating of air quality or symptoms.	-	**Strengths:** Ss blinded, grounded bed **Weaknesses:** Test subject randomization not reported.
	(+)	5.0-10.0 x 10^3	1-2 hrs		Some subjects reported irritation of respiratory tract. Authors point out that the "experiments were made during the winter, when upper respiratory symptoms were common."	
	(-)	2.0-4.0 x 10^3	2 x 2 hrs/day for 14 days	No effect on respiration rate of malnourished infants.		
Lefcoe, 1963	(-)	1.25 x 10^5	4 hrs	Pulmonary function tests (forced vital capacity, forced expiratory volume, and maximum mid-expiratory flow rate), symptoms of bronchial asthma.		**Strengths:** Ion measurements taken every hr during control, exposure and post-exposure periods; most subjects tested in 3 separate runs on separate days; values reported as percentage of control mean values. **Weaknesses:** Blinded analysis and test subject randomization not reported, insufficient data provided for adequate evaluation.
	(+)	1.25 x 10^5	4 hrs			
Blumstein et al., 1964	(-)	1.0 x $10^{4.}$	30 min, 5 consecutive days	Six measures of pulmonary function, subjective symptom relief, did not differ by exposure treatment in patients with respiratory allergy, asthma, or pulmonary emphysema.	None	**Strengths:** Double blind, direct evaluation of placebo effect
	(+)	1.0 x 10^4				

Study Author(s), Year	Ion Polarity	Ion Concentration (ions/cm^3)	Exposure Duration	Parameters NOT Affected by Ion Exposure	Effects Reported	Design QA
Motley and Yanda, 1966	(-)	5.0×10^5 per mL	33 patients exposed for 3 hrs and 13 patients exposed for 1 hr	Lung volume measurements and ventilation factors	No significant effects reported	**Strengths:** Participants served as their own controls, relatively large number of Ss, filtered air. **Weaknesses:** Insufficient description of study methods; no blinding of study participants or study investigators; no air filtration in studies conducted at home; no discussion of study participant selection.
	(-)		7-12 hrs/day for 14 days	Lung volume measurements and ventilation factors. Note that, in six of the cases, lung volume studies were repeated after a second 2 wks' use at home.	No significant effects reported	
	(+) and (-)		30 min	Arterial blood saturation, CO_2 content, arterial pO2, arterial CO_2, pH, minute ventilation, tidal volume, oxygen uptake, oxygen percent extracted from the inspired air breathed, calculated mean alveolar pO2, alveolar-arterial pO2 difference, effective tidal air percent, and carbon monoxide diffusing capacity.	No significant effects reported	
Palti et al., 1966	(-)	1.0×10^4	8 - 39 hrs	-	Reduced bronchial spasm and lowered respiration rate	**Strengths:** Investigators blind to treatment; no washout period reported. **Weaknesses:** Insufficient description of study methods, participant selection and results, exposed and control Ss from different hospitals; blinding of study participants not reported; appears to be no wash-out period.
	(+)		3 - 21 hrs	-	Initiated bronchial spasm	
	(-)		12-38 hrs	-	Initiated bronchial spasm	
	(+)		10-33 hrs	-	Reduced bronchial spasm	
McDonald et al., 1967	(-)	1.0×10^6	45 mins	Respiration rate not different from control		**Strengths:** current of Ss to ground monitored **Weaknesses:** Ss and analysis not blinded and test subject randomization not reported.
	(+)		45 mins	Respiration rate not different from control		

Study Author(s), Year	Ion Polarity	Ion Concentration (ions/cm^3)	Exposure Duration	Parameters NOT Affected by Ion Exposure	Effects Reported	Design QA
Jones et al., 1976	(-)	NR	4 wks placebo; 8 wks active; 4 wks no ionizer	No significant difference among three time periods in clinical-subjective combined score. Effects measured as morning and evening PEFR scores.		**Weaknesses:** Not randomized. No control group, wide age range, small numbers
Albrechtsen et al, 1978	(-)	8×10^3	8 min	Respiratory rate		**Strengths:** Measured ion mobility, grounded Ss, constant humidity, temperature; controlled, well-described experiment **Weaknesses:** No selection criteria
	(+)	1×10^4	8 min			
	(-)		15 min	Respiratory rate		
	(+)		15 min			
Ben Dov, 1983	(-)	$4.0\text{-}10.0 \times 10^5$	2, 6 min exercise tests, 3-24 hrs apart	Breathing ionized air for 10 mins did not significantly change lung function (FEV1) of children.	Breathing ionized air significantly reduced exercise induced asthma/bronchial reactivity.	**Strengths:** Double blind study **Weaknesses:** No details of severity reported, inclusion and exclusion criteria not stated, not randomized, ozone contamination "negligible" but even trace amounts would have been inhaled because of mouthpiece.
	(-)	$4.0\text{-}10.0 \times 10^5$	histamine challenge tests 24 hrs apart	Histamine results inconclusive		
Danzler et al., 1983	(-)	1.0×10^5	6 hrs	FEV and somatic symptoms reported did not differ significantly from baseline or between (-) and (+) ion exposures.		**Strengths:** Double blind study; measured ions and grounded Ss; pulmonary measurements taken at 15, 30, 120, 240, and 360 min during exposures **Weaknesses:** No selection criteria and control period, data on symptoms not quantified
	(+)	1.0×10^5	6 hrs			

Study Author(s), Year	Ion Polarity	Ion Concentration (ions/cm^{3})	Exposure Duration	Parameters NOT Affected by Ion Exposure	Effects Reported	Design QA
Nogrady and Furnglass, 1983	(-)	>1.5 x 10^5	2 x 8-wk periods with 4-wk washouts; ioniser active from 10PM-8AM daily	PEFR; symptom score; and bronchodilator consumption		**Strengths:** Double-blind; dust measurements taken; included a wash-out period **Weaknesses:** Randomization method unclear; differences in baseline PEF; non-validated symptom scale
Wagner et al., 1983	(-)	500-1,600	32 days	PEFR (4 tests/day) for 48 days		**Weaknesses:** No selection criteria; single blind; ions measured at a single regional monitor distant from S residence; analyses incomplete; (-) ions measured but NR.
	(+)	500-1,600	32 days			
Kirkham et al., 1984	(-)	NS	4 wks, 8 hrs per night	Lung 'mechanics' measure by whole body plethysmography; gas mixing (nitrogen washout)		**Strengths:** Ss blinded **Weaknesses:** Summary results only, no test results reported; method of blinding not described; not randomized; diagnostic criteria not given; no subjective information after testing; control number not reported; no measures of ion concentration.
Lipin et al., 1984	(+)	5-10 x 10^5	10 min, then 6 min with exercise, repeated in 24 hrs	Exercise tests for minute ventilation, oxygen consumption, baseline FEV in asthmatic children	Post exercise fall in FEV1 significantly greater in exposed. 8/12 subjects developed more exercise-induced asthma and two subjects less, two no difference.	**Strengths:** Double blind; exposure delivered direct to mouth **Weaknesses**: No clear randomization. Inclusion and exclusion criteria not given.
Finnegan et al., 1987	(-)	1.84 x 10^3	6-8 wks	Daily ratings of personal comfort (5 measures) and environmental comfort (4 measures); upper respiratory symptoms	Proportion of Ss with upper respiratory tract infections during exposed period > control period	**Strengths:** Daily ion measurements; Ss blinded; ratings adjusted for temp and RH **Weaknesses:** No random assignment; no symptom data reported

Study Author(s), Year	Ion Polarity	Ion Concentration (ions/cm3)	Exposure Duration	Parameters NOT Affected by Ion Exposure	Effects Reported	Design QA
Reilly and Stevenson, 1993	(-)	1.72×10^5	30 min pre-test + 40 min during test	No differences in VO2 or VE at submax or maximal exercise with (-) ions; difference in VO2 and VE between rest and both exercise conditions significantly greater with (-) ions	Oxygen uptake (VO2) and ventilation (VE) significantly reduced at rest with (-) ions	**Strengths:** Ss blinded **Weaknesses:** Not known if analyses conducted in blinded manner or if test subjects were randomized; evaluations at 1:30, 10:00, 14:00 and 18:00 hrs; perceived exertion during 40 min submax and maximum exercise; significant inter-subject variability in all physiological measures.
Warner et al., 1993	NR	NR	6 wks of active ioniser in home followed by 6 wks of placebo ioniser in home	PEFR, night time wheeze, daytime wheeze, nighttime cough, daytime cough, daytime activity, medication		**Strengths:** Double-blind; placebo-controlled **Weaknesses:** Randomization method unclear; residential exposure only

Abbreviations key: f = female; fev = forced expiratory volume; hr = hour; m = male; min = minute; mo = month; NS = not specified; NR = not reported; PEF = peak expiratory flow; PEFR = peak expiratory flow rate; pO2= partial pressure of oxygen; VO2 = oxygen update; VE = ventilation; wk = week; yr = year

Table 2-2. Studies of air ions and mood

Study Author(s), Year	Ion Polarity	Ion Concentration	Exposure Duration	Parameters NOT Affected by Ion Exposure	Effects Reported	Design QA
Silverman and Kornbleuh, 1957	(-)	NR	30 min		Transient decrease in EEG alpha frequency in most subjects; half of subjects reported dryness of mouth and upper respiratory tract, relaxation and sleepiness with ionization (slightly more frequent for (-) than (+) ion exposure)	Blinded analysis and test subject randomization not reported; small sample size
	(+)		30 min			
McGurk, 1959	(-)	8.0 x 10^3	5 hrs		A significant percent of subjects appeared to detect ionization condition despite blinding and reported more pleasant feelings.	**Strengths:** Ss blind to exposures **Weaknesses:** Blinded analysis and test subject randomization not reported.
	(+)	8.0 x 10^3	2 hrs		Subjects reported more unpleasant feelings.	
Yaglou, 1961	(-) / (+)	5.0-10.0 x 10^3	1-2 hrs	No effect on subjective rating of mood or symptoms		**Strengths:** Ss blind to exposures **Weaknesses:** Blinded analysis and test subject randomization not reported.
	(-)	2.0-4.0 x 10^3	2 x 2 hrs/day for 14 days		Infants appeared quieter and cried less.	Blinded analysis and test subject randomization not reported.
Assael et al., 1974	(-)	3.5 x 10^5	45 mins	EEG changes not observed in patients given tranquilizers	Increase amplitude and synchronization of EEG with decrease in alpha frequency. Subjective reports of relaxation with ionization	**Strengths:** Subjects given tranquilizers first tested with placebo and double blinded. **Weaknesses:** All results are in the form of EEGs. The authors interpret a decrease in alpha frequency as relaxation.

Study Author(s), Year	Ion Polarity	Ion Concentration	Exposure Duration	Parameters NOT Affected by Ion Exposure	Effects Reported	Design QA
Sigel, 1979	(+)/(-)	1.0×10^5	2 hrs	Ion exposure (+) or (-) did not affect mood ratings relating to tension, depression, anger, fatigue, or confusion.	Mood alterations: higher vigor and friendliness in ionized subjects	**Strengths:** Randomly assigned to exposure conditions, data presented as mean values for each 15-min interval during exposure period **Weaknesses:** Blinded analyses not reported
Charry and Hawkinshire, 1981	(+)	$2.0\text{-}3.0 \times 10^4$	1.5 hrs positive ion exposure, 3-day wash-out period, 1.5 hrs ambient exposure		Mood alterations as indicated by decreased attention and task involvement and increased tension and anxiety. A measure of low-lability autonomic response identified by decreased skin conductance (arousal) High lability displayed increased skin conductance.	**Strengths:** Participants blind to treatment; controlled trial; relatively large number of participants **Weaknesses**: Insufficient description of study methods
Tom et al., 1981	(-)	16,160 ions/cm^3	15 mins	No effect on mood, sociability, or relaxed state subtests		**Strengths:** Controlled experiment; random assignment; double-blinded; temperature and humidity controlled; time of day controlled **Weaknesses:** Control n and experimental n not specified; baseline characteristics of total group only, not control and experimental Ss; S pool not described & exclusions & withdrawals not mentioned; randomization method not stated; outcome variable--one item on a questionnaire with 5 items total--no information concerning the reliability and validity of the questionnaire.

Study Author(s), Year	Ion Polarity	Ion Concentration	Exposure Duration	Parameters NOT Affected by Ion Exposure	Effects Reported	Design QA
Buckalew and Rizzuto, 1982	(-)	NR	6 hrs	Anxiety (TMAS)	Subjective feelings of relaxations. Reductions in irritability, depression and tenseness. Increases in calmness and stimulation. Improved mood or psychological states.	**Strengths:** Double blind. Exposed and controls matched on age, education, smoking. **Weaknesses**: Ion concentration not reported. Mood index was self report. No base line data either group.
Baron et al., 1985	(-)	4 x 10^4/cm^3 7.0-8.0 x 10^4/cm^3	20 min	Non-angry depression ration: no difference was noted in the pleasantness scale although only the raw scores were shown.	For the non-angry subjects: Feelings of depression, anger, and fatigue "generally" decreased as the ion concentration increased. For the angry subjects: Feelings of depression, anger, and fatigue increased as the ion concentration increased. Results interpreted as increased arousal or activation.	Randomization method: no mention of randomization. Blinding: subjects were blinded. Subject pool: male undergraduates fulfilling a course requirement. Excluded: not mentioned. Withdrawals: not mentioned. Baseline characteristics: all male undergraduates. **Strengths**: Controlled experiment; subjects were blinded; ion concentrations measured; Ss grounded. **Weaknesses:** Researchers were not blinded; unclear if Ss were randomly assigned to the ion groups; small number of Ss.
Dantzler et al., 1983	(-) (+)	6-10 x 10^4	6 hrs	Three questionnaires on symptom and mood changes, including mood, energy level, sociability, tension level, and concentration.		**Weaknesses:** No selection criteria; double blind; measured ions and grounded Ss; no control period; questionnaire data NR; questionnaires not validated.
Deleanu and Stamatiu, 1985	(-)	1-1.5 x 10^4/cm^3	Daily, 10-30 days, 15 min or up to 50 min	Aggravation of psychiatric symptoms	Exposure ameliorated symptoms reported by patients for astenia, depression. Favorable results for sleep normalization.	**Weaknesses**: No control groups, no mention of blinding, results subjective, qualitative, descriptive. No tabular results. Results not explained clearly.
Finneagan et al., 1987	(-)	1.84 x 10^3	6-8 wks	Daily ratings of 5 personal comfort and 4 environmental comfort ratings		**Strengths:** Daily ion measurements; ratings adjusted for temp and RH. **Weaknesses:** Ss were workers in a 'sick bldg'; no random assignment; no symptom data reported.
	(-)	1.84 x 10^3	6-8 wks			

Study Author(s), Year	Ion Polarity	Ion Concentration	Exposure Duration	Parameters NOT Affected by Ion Exposure	Effects Reported	Design QA
Giannini et al., 1986/1987	(+)	2 -2.3 x 10^3/cm^3	2 hours	BRPS, psychiatric scale.	Rise in symptoms of anxiety and excitement.	**Strengths:** Double blind, 2 raters. **Weaknesses:** Subjective data only
Giannini et al.., 1986	(-)	NR	20 min	Anxiety and tension in prionization with anions.	Cations increase anxiety, suspicion, and excitement. Follow up exposure to anions reduced anxiety tension, suspiciousness and excitement.	**Strengths:** double blind. BPRS for all subjects. **Weaknesses:** Tables of results not consistent with method in text. Overall mean of BPRS not reported.
	(+)	2.x 10^3/cm^3	20 min			
Hawkins, 1981	(-)	2-3.5x 10^3			Ss rated (-) ion periods as slightly warmer and fresher ENV & give slightly higher PERS ratings for warmth and alertness; higher ratings of comfort, pleased alert during night shift in area 3.	Double blind; ion measurements; data from area 2 partial reported; inadequate methods and analysis.
	(+)	50-125	8 wks on; 4 wks off (areas 1 & 2); 4 wks on; 8 wks off (area 2).			
Hedge and Collins, 1987	(-)	2x 10^4 ions/cm^3 placebo 2.5x10^2	3 consecutive working days	Stress, arousal, cognitive task performance	No effects reported.	Validated tests used for mood, both a control and a placebo used: randomization of the 3 treatments for each individual. Double blind until ionization turned on.
Lips, 1987	(-)	5 x 10^4ions/cm^3 of air	Ionisers continuously turned on 9AM-5PM	Thermal comfort scores	Subjects' assessments of both their own well-being and the quality of the environment improved significantly.	**Strengths:** Controlled trial. **Weaknesses:** No randomization; outcome based on self report; small study size.

Study Author(s), Year	Ion Polarity	Ion Concentration	Exposure Duration	Parameters NOT Affected by Ion Exposure	Effects Reported	Design QA
Misiaszek et al., 1987	(-)	4-6 x 10^4 sm ions 50-1000 med ions, 50-4000 lg ions	1 hr		All subjects fell to sleep, reported being calm afterwards; manic behavior reappeared 5-10 min after treatment	No control exposures; unblinded study; small sample size (4).
		5-7 x 10^4 sm ions, 70,000, 50-3200 med ions, 50-7000 lg ions	1.5 hrs		3/4 subjects fell to sleep, 1 subject appeared less agitated; manic behavior reappeared 5-10 min after treatment	Small sample size (4).
Reilly and Stevenson, 1993	(-)	1.72 x 10^5	30 mins pre-test + 40 mins during test	No effect on pre- or post-exercise anxiety, state anxiety or perception of effort.		Subjects blinded to exposure conditions; not known if analyses conducted in blinded manner or if test subjects were randomized; no description of methods or quantitative summary of results.
Terman and Terman, 1995	(-)	1.0 x 10^4 2.7 x 10^6	20 min x 20 days		Lower scores on the SIGH-SAD scale indicating improvement in depression. Improvement noted on both subscales.	**Strengths:** Experiment; random assignment; apparently double blinded. **Weaknesses:** Subject pool not described; excluded & withdrawal of Ss not mentioned**; s**ignificant difference in ages between groups; randomization method not stated; Ss self-exposed at home; ion concentrations not measured; in the procedure section, two outcome scales were described but in the results section only one was discussed.

Study Author(s), Year	Ion Polarity	Ion Concentration	Exposure Duration	Parameters NOT Affected by Ion Exposure	Effects Reported	Design QA
Terman et al., 1998	(-)	1.0×10^4 ions/cm^3 10,000 2.7×10^6 ions/cm^3	30 min x 10-14 days	Improved depression rating of 16-20% and 5-10% remission rate. This response was described as "ineffective."	Improved depression rating of 42-50% and 20-40% remission rate. Described as a "small effect" in P1 and "large effect" in P2.	**Strengths**: Raters of depression status were blinded; several tests given to volunteers--must fulfill certain criteria to be included. **Weaknesses**: No measurements of ion concentration; randomization method not stated; S characteristics not described; unclear if the subjects receiving the negative air ionization were blinded; Ss self-exposed at home; the absence of a relation between the Ss expectation of benefit and result is contrary to experience; baseline characteristics given for the total group--not individual treatment groups.
Nakane et al., 2002	(-)	$5.5\text{-}7.3 \times 10^3$	Either 40 minutes during task or 30 minutes post-task		(-) ions during task or during post-task recovery period reduced State-Trait Anxiety Inventory, Anxiety State (STAI-S) scores.	**Strengths:** Exposures randomized and subjects blinded to exposure conditions. **Weaknesses:** Small sample size (n = 4).
Iwama et al., 2004	(-)	1000 parts/mL	Length of surgery; exact time not specified		Degree of tension reported by study participants during first or latter half of surgery significantly reduced among ion-exposed group.	**Strengths:** Controlled trial. **Weaknesses:** No blinding of patients reported; no randomization; outcome based on self report.

Study Author(s), Year	Ion Polarity	Ion Concentration	Exposure Duration	Parameters NOT Affected by Ion Exposure	Effects Reported	Design QA
Goel et al., 2005	(-)	High density=4.5 x 10^{14} ions/s Low-density, control group=1.7 x 10^{11} ions/s	1 hr upon wakening for 5 wks	Melatonin onset, sleep onset, sleep midpoint, and sleep offset	Improved SIGH-SAD total score, Hamilton subscale, and atypical symptom subscale	**Strengths:** Controlled double-blind trial. **Weaknesses:** Effects compared to low, negative ion exposure, rather than no exposure; small sample size.
Goel and Etwaroo, 2006	(-)	High density=4.5 x 10^{14} ions/s Low-density, control group=1.7 x 10^{11} ions/s	30 mins for three consecutive evenings	Likert scale ratings of perceptual characteristics and some moods (anger, vigor, tension, fatigue, and confusion).	Reduced depression scores after 15-30 min	**Strengths:** Controlled trial; relatively large number of participants; controlled for seasonal effects. **Weaknesses:** No blinding; effects compared to low, negative ion exposure, rather than no exposure.
Terman and Terman, 2006	(-)	1.7 x 10^{11} ions/s 4.5 x 10^{14} ions/s	93 minutes	The Atypical Symptom Scale did not show significant group effect with raw scores but did when percentage improvement was used.	For the SIGH-SAD scores the improvement in the low-density ion group was significantly lower than the high-density ion group (and other non-ion groups as well). The Hamilton-D scale also showed a significant group effect.	**Strengths:** Random assignment of Ss; raters blinded; extensive entry criteria **Weaknesses:** Randomization method not stated; Withdrawals- 126 subjects entered; 118 completed and reasons given. 99 were analyzed (additional cases were excluded after the data was analyzed); Unclear as to the validity of the removal of subjects after initial analysis has been completed--rationale was given.

Study Author(s), Year	Ion Polarity	Ion Concentration	Exposure Duration	Parameters NOT Affected by Ion Exposure	Effects Reported	Design QA
Giannini et al., 2007	(-)	$3 \times 10^3/cm^3$	60 mins	No effect of order for treatment versus sham. No significant difference in pre-and post-treatment scores for individual items.	Significant reduction in manic symptoms on BPRS score.	**Strengths**: Two raters for BRS. **Weaknesses**: No biochemical measures. Subjects varied in days under med treatment. Began with 24 subjects but ended with 20, no explanation.
Watanabe et al., 1997	(-)	2.0×10^4 ions/cm^3	10 mins	No difference was noted in the pleasantness scale although only the raw scores were shown.		**Strengths:** Controlled experiment; S pool not described & exclusion and withdrawals of Ss not described; Ss were blinded; time of day, temperature, humidity were controlled. **Weaknesses:** Researchers were not blinded; subjects were both control and experimental groups; "Pleasantness scale" was just one of four items that were asked by an interviewer. No information regarding the reliability and validity of the questionnaire.
Malcolm et al., 2009	(-)	NR	30 mins prior to testing + 60 mins during testing	Facial expression recognition and dot-probe tasks.	Association between Beck Depression Inventory score and treatment; increased recall and recognition of positive terms versus negative terms	**Strengths:** Subjects randomly assigned to exposure groups and blinded to exposure conditions. **Weaknesses:** Not reported if analyses conducted in blinded manner; Insufficient description of study methods.
Flory et al., 2010	(-)	4.0×10^3 (control) $\geq 2.0 \times 10^6$ (exposed)	30 mins x 12 days	Ratings of depression – two scales (HAM-D, BDI); remission rate criteria; symptoms of SAD; comparisons of ion groups to placebo group (red light) shows strong placebo effect.		**Strengths**: Measurements of ion and ozone concentrations; independent treatment groups; multiple measures of symptoms; inclusion & exclusion criteria; Ss randomly assigned to test groups; assessment of placebo effects. **Weaknesses:** Ss assembled and tested over 5 yrs; no true unexposed control group ; post-hoc inappropriate merging of groups for some analyses; no statistical analysis of % subjects; no validation of treatment expectation questionnaire.

Abbreviations key: hr = hour; m = medium; min = minute; n = number; NR = not reported; Ss= subjects; wk = week.

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Notice

At the request of Manitoba Hydro, Exponent conducted specific modeling and evaluations of components of the electrical environment of the Bipole III project. This report summarizes work performed to date and presents the findings resulting from that work. In the analysis, we have relied on geometry, material data, usage conditions, specifications, regulatory status, and various other types of information provided by the client. We cannot verify the correctness of this input data, and rely on the client for the data's accuracy. Although Exponent has exercised usual and customary care in the conduct of this analysis, the responsibility for the design and operation of the project remains fully with the client.

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 investigation 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 herein 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.

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Acronyms and Abbreviations

AC	Alternating current
AM	Amplitude modulated
AN	Audible noise
BPA	Bonneville Power Administration
Corridor	The Henday-Keewatinow Transmission Corridor
dB	Decibels
dB-A	Decibels on the A-weighted scale
DC	Direct current
EPRI	Electric Power Research Institute
FM	Frequency modulated
Hz	Hertz
km	Kilometre
ICES	International Committee on Electromagnetic Safety
ICNIRP	International Commission on Non-Ionizing Radiation Protection
kV	Kilovolts
m	Metre
mHz	Megahertz
mT	millitesla
MVA	Megavolt ampere
MW	Megawatt
NRPB	National Radiological Protection Board
RN	Radio noise
ROW	Right-of-way
rms	Root mean square
SPL	Sound pressure level
µPa	Micropascal
µVm	microvolt/metre

Introduction

Manitoba Hydro has proposed to improve reliability of the province's electricity supply by constructing a new ±500 kilovolt (kV) overhead direct current (DC) transmission line known as Bipole III. The 1,364 kilometre (km) transmission line will connect a new converter station in northern Manitoba northeast of Gillam (Keewatinoow) to a new converter station east of Winnipeg at the Riel Station site.

To transfer power from northern generating stations to the Keewatinoow Converter Station, Manitoba Hydro is proposing the construction of five 230-kV alternating current (AC) transmission lines in the Henday-Keewatinoow Transmission Corridor (the Corridor). One of these lines will run between the existing 230-kV switchyard at the Long Spruce Generating Station and a new 230-kV switchyard at the site of the new northern converter station, while the four other lines will connect the existing 230-kV switchyard at the Henday Converter Station to the new 230-kV switchyard at the site of the new northern converter station. Together, these 230 kV AC lines are referred to the Northern collector lines. In addition, a 138-kV line will be extended along the east side of the corridor to provide construction power.

This report summarizes calculations of the electrical environment around the existing and proposed AC transmission lines that are part of the Bipole III transmission project. Modeling methods to determine post-construction levels of AC EMF, audible noise (AN), and radio noise (RN) are discussed in Section 1. The results of these calculations are presented in Section 2. Assessment criteria and conclusions are outlined in Section 3. The input data used for modeling the AC corridor is presented in Appendix A. And, finally, Exponent's report on EMF and health, "Research on Extremely Low Frequency Electric and Magnetic Fields from Alternating Current Transmission Lines—Summary Evaluation of the Evidence," prepared in February, 2011, is incorporated as Appendix B.

Methods

AC electric and magnetic field calculations

The design parameters and operating conditions used in the modeling of the electrical environment around the proposed 230-kV transmission lines in the Corridor are summarized in Appendix A.

Pre- and post-construction AC EMF levels were calculated using computer algorithms developed by the Bonneville Power Administration (BPA), an agency of the U.S. Department of Energy (BPA, 1991). These algorithms have been shown to accurately predict AC EMF levels measured near power lines. The inputs to the programs are data regarding voltage, current flow, phasing, and conductor configurations. The fields associated with power lines were estimated along profiles perpendicular to lines at the point of lowest conductor sag, i.e., closest to the ground. The program assumed that the transmission conductors were at maximum sag for the entire distance between structures and flat terrain and currents were balanced on all phases. An overvoltage condition of 5 percent for all AC transmission lines was assumed for the electric field calculations.

The EMF levels were calculated at 1 m (3.28 feet) above ground, in accordance with IEEE Std. 0644-1994, as the RMS value of the field ellipse. Additional analyses also were performed to determine which phasing of the 230-kV lines proposed for the Corridor would result in minimum magnetic field levels at the ROW edge. This would provide the option for Manitoba Hydro to select an optimal phasing for the circuits, a low-cost approach to minimize magnetic field levels consistent with the World Health Organization's recommendations (WHO, 2007).

AC audible noise calculations

The conductors of 230-kV transmission lines are designed to produce minimal AN under ideal conditions; however, protrusions on the conductor surface—particularly water droplets on or dripping off the conductors—can cause the electric field intensity at the conductor surface to exceed the breakdown strength of air, producing AN. Therefore, unlike DC transmission lines, AN from AC transmission lines is generally a foul-weather (wet-conductor) phenomenon. Wet conductors can occur during periods of rain, fog, snow, or ice. This AN can be characterized as a hissing, crackling sound that may be accompanied by a 120-Hz hum.

Foul-weather AN levels for the lines in dBA units weighted by the sensitivity of the human ear were calculated using computer algorithms developed by the BPA. Fair weather levels were calculated by the subtraction of 25 dBA from the calculated foul-weather values as recommended by the BPA (BPA, 1991).

An altitude of 250 m (~820 feet) and the height of a sound receiver of 1.52 m (5 feet) were assumed for the calculation of AC AN. AN levels will increase at higher altitudes at a rate of approximately 1 dB per 300 m.

AC radio noise calculations

Corona caused by high electric field levels at a conductor surface induces impulsive currents along a transmission line. These induced currents, in turn, cause wideband electric and magnetic noise fields that can affect radio and television reception. RN can produce interference to an amplitude-modulated (AM) signal such as a commercial AM radio station's audio signal or the video portion of the present analog television station's signal, which is expected to be converted to digital in Canada in 2011. Frequency modulated (FM) radio stations and the audio portion of a television station (which is also FM) are generally not affected by RN from a transmission line.

Weather has a large influence on corona-generated RN levels, as it does for AN levels. Similarly, altitude elevates RN levels as well.

RN is measured in units of dB based on its field strength referenced to a signal level of 1 microvolt/metre (μV/m). The levels of RN were calculated at a frequency of 0.5 megahertz (MHz) for the proposed configuration in foul weather and referenced to a CISPR-type meter.

Modeling Results for the 230-kV Transmission Lines in the Corridor

Bipole III requires four new 230-kV lines between the Keewatinoow converter station and the Henday substation, and one 230-kV line between the Keewatinoow converter station and the Long Spruce substation. In addition, a 138-kV line will be extended along the east side of the Corridor to provide construction power (Figure 1).

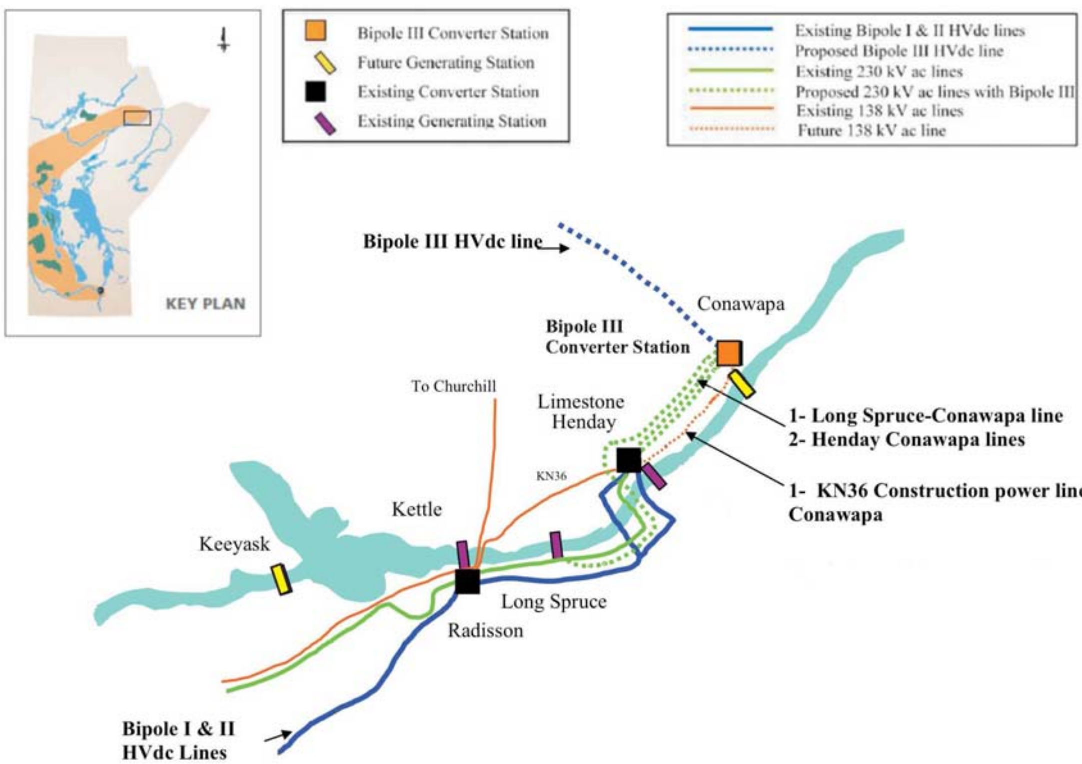

Figure 1. Location of existing 230-kV AC transmission lines and proposed Bipole III AC 230-kV transmission lines

The configuration of the corridor with all six transmission lines is depicted in Figure 2. Appendix A contains the conductor type, position, and loading used to calculate the AC magnetic field, AC electric field, AN, and RN along a transect perpendicular to the corridor at midspan.

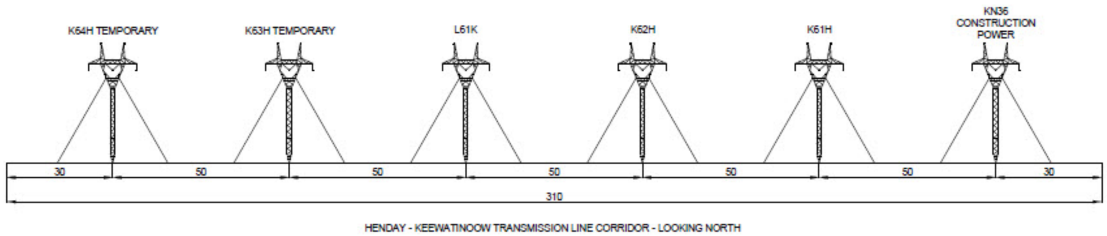

Figure 2. Configuration of the corridor (view facing north).

From west to east, five 230-kV circuits are designated K64H, K63H, L61K, K62K, and K61H. On the east side of the corridor (right side of the figure, a 138-kV circuit designated KN36 provides construction power.

An analysis of the magnetic field at the edge of the ROW for different conductor phasing yielded the optimal choice for phasing for the six transmission lines to minimize magnetic fields outside the Corridor.[1] Figure 3 depicts the modeled magnetic field profile, incorporating this phasing, at average loading with Keeyask generation and the Keewatinoow converter station operating. This loading scenario assumes no outages of the DC Bipole lines that would change loadings on the AC lines. The magnetic field values calculated at the edge of the ROW for average loading and nine additional cases are summarized in Table 1. In all loading cases, the 138-kV line (KN36) was modeled with a 30 megavolt ampere (MVA) loading.

Calculated AC electric-field, AN, and RN profiles are depicted in Figures 4-6, above tabulated levels calculated at particular locations (Tables 2-4). For the conductor positions reported in Appendix A, the AC electric field, AN, and RN levels do not change with loading condition.

[1] The optimal phasing identified for the loadings provided is CBA/ABC/CBA/ABC/ABC/CBA (left to right in Figure 3).

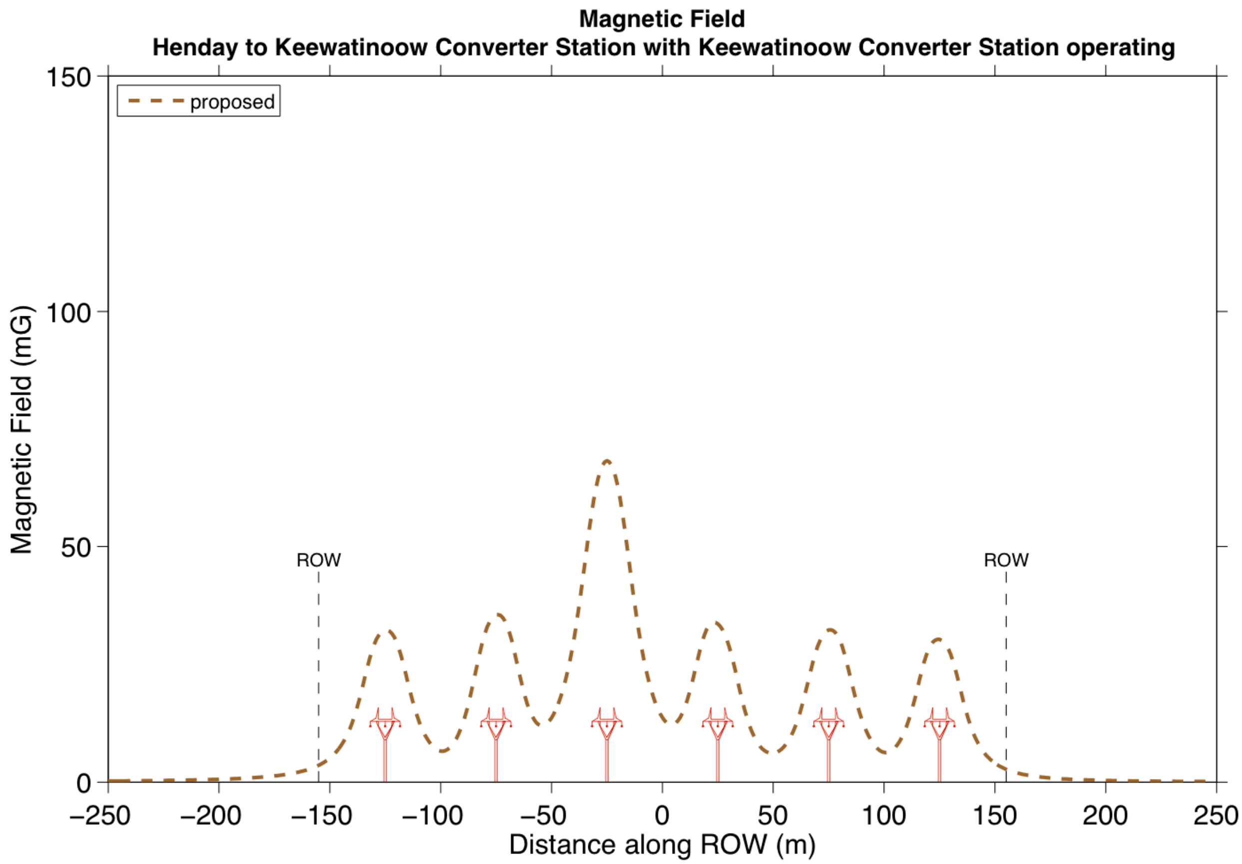

Figure 3. Calculated magnetic field profile under average loading conditions with Keeyask generation and the Keewatinoow Converter Station operating.

Table 1. AC magnetic field (mG) at specified locations

Quantity	Loading condition	-ROW	Maximum on ROW	+ROW
Magnetic Field (mG) With Keeyask generation and the Keewatinoow converter station operating	Bipole III 2,000 MW and 2500 MW, no outages, Average	3.6	68.2	2.7
	Bipole III 2,000 MW and 2500 MW, no outages, Peak	5.3	101.8	2.5
	Bipole III 2,000 MW, HVDC outages, Peak	7.0	127.8	2.3
	Bipole III 2,500 MW, HVDC outages, Peak	16.0	211.9	1.2
Magnetic Field (mG) Without New Generation	Bipole III 2,000 MW, no outages, Average	8.5	96.2	1.8
	Bipole III 2,000 MW, no outages, Peak	12.6	143.7	1.4
	Bipole III 2,500 MW, no outages, Average	8.5	95.2	1.8
	Bipole III 2,500 MW, no outages, Peak	12.6	142.1	1.3
	Bipole III 2,000 MW, HVDC outages, Peak	23.3	238.6	2.0
	Bipole III 2,500 MW, HVDC outages, Peak	30.1	310.3	3.4

Electric fields

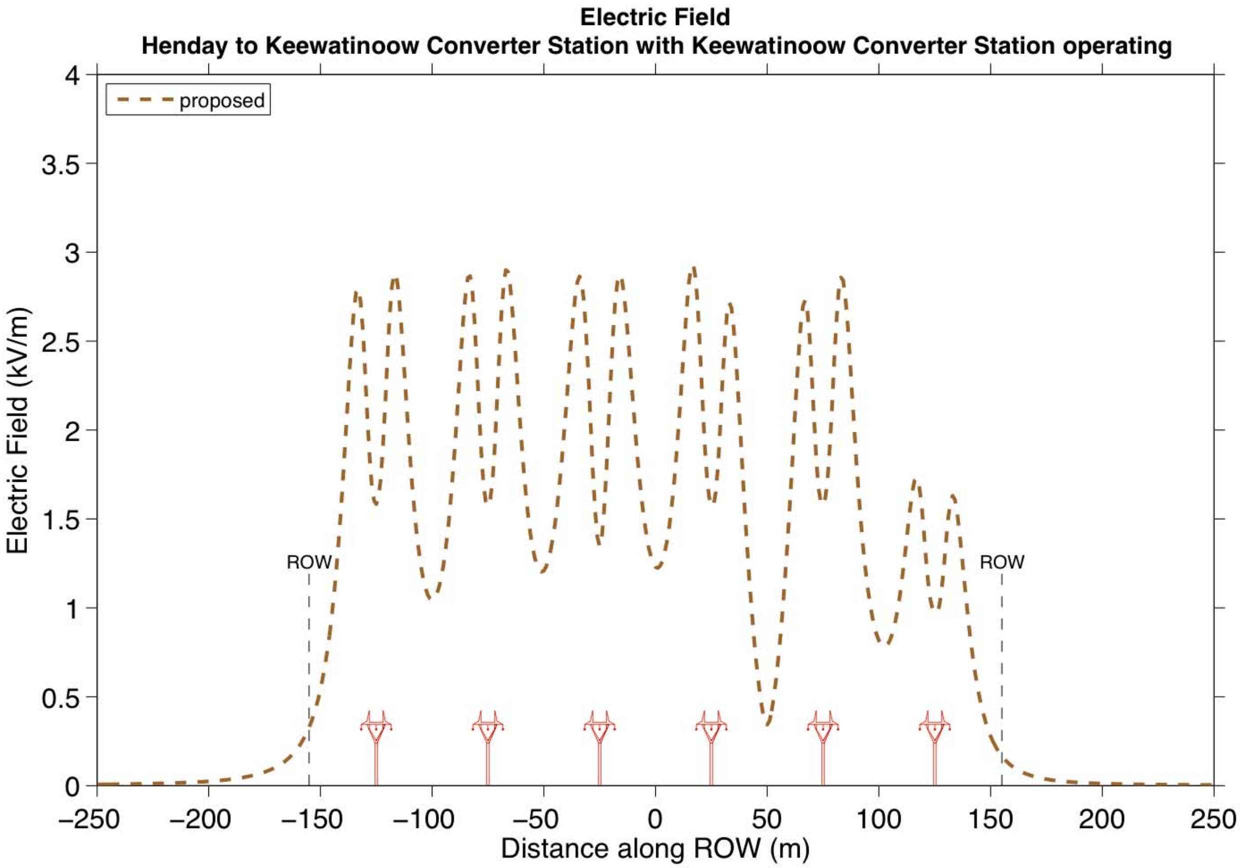

Figure 4. Calculated AC electric field profile for the proposed cross-section in the Corridor

Table 2. Electric field (kV/m) for the transmission corridor

Quantity	Loading condition	-ROW	Maximum on ROW	+ROW
Electric Field (kV/m)	Any	0.33	2.93	0.17

Audible noise

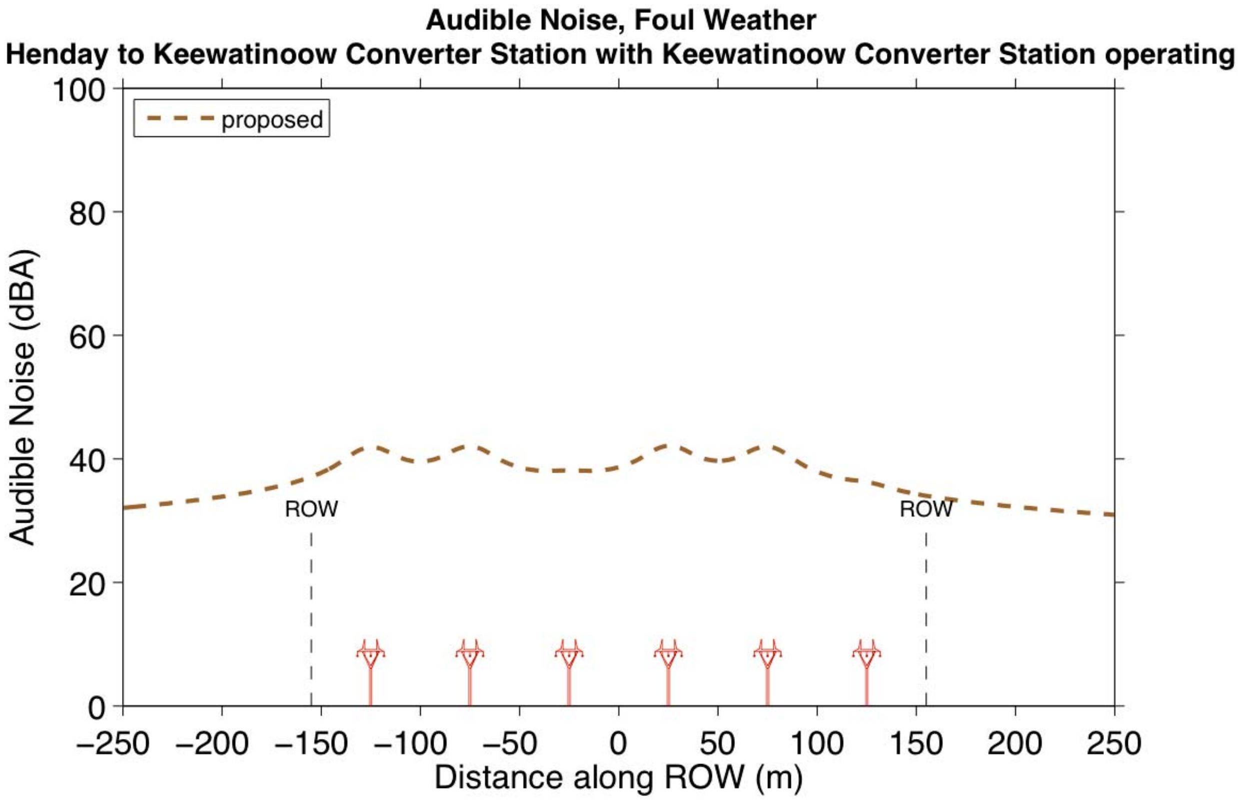

Figure 5. Calculated AC AN profile in foul weather conditions for the proposed cross-section in the Corridor. AN under fair weather conditions will be 25 dbA lower than the levels shown above.

Table 3. Audible noise from the AC lines at specified locations under fair and foul weather

	Fair weather		Foul weather	
Quantity	-ROW	+ROW	-ROW	+ROW
Audible Noise (dBA)	12.1	9.0	37.1	34.0

Radio noise

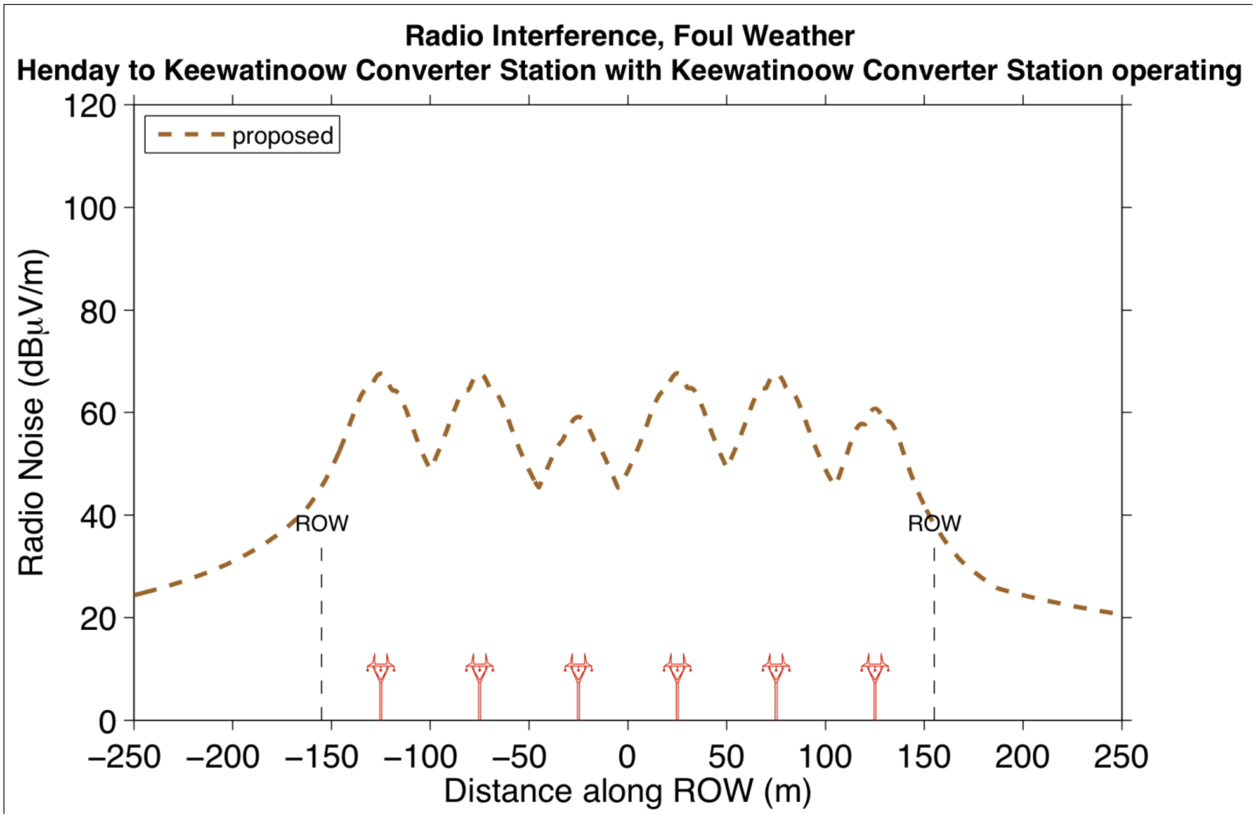

Figure 6. Calculated AC RN profile in foul weather conditions for the proposed cross-section in the Corridor calculated at 0.5 MHz. RN levels under fair weather will be 17 dBμV/m lower than those shown above.

Table 4. Radio noise from the AC lines at specified locations under fair and foul weather

	Fair weather		Foul weather	
Quantity	-15 m beyond western-most conductor	+15 m beyond eastern-most conductor	-15 m beyond western-most conductor	+15 m beyond eastern-most conductor
Radio Noise (dBμV/m)	34.6	27.4	51.6	44.4

Assessment Criteria and Conclusions

AC electric and magnetic fields

Guidelines for exposure to AC electric and magnetic fields have been recommended by ICNIRP and the International Committee on Electromagnetic Safety (ICES) to address health and safety issues (ICNIRP, 2010; ICES, 2002). The ICNIRP guideline limits are lower and recommended electric field exposures less than 4.2 kV/m and magnetic field exposures less than 2,000 mG for the general public. The levels of EMF from the new 230-kV and 138-kV transmission lines are calculated to be well below the ICNIRP and ICES guidelines for human exposure. A review and evaluation of current research on EMF and health relevant to exposures below these guidelines is provided in the companion report "Research on Extremely Low Frequency Electric and Magnetic Fields from Alternating Current Transmission Lines—Summary Evaluation of the Evidence." The report states:

> The current consensus among the numerous national and international scientific agencies that have reviewed this extensive body of research (including the World Health Organization, the International Agency for Research on Cancer, the National Institute of Environmental Health Sciences, the Health Protection Agency of Great Britain, and the Federal-Provincial-Territorial Radiation Protection Committee of Canada) is that there is no known relationship between exposure to ELF EMF at the levels generally found in residential and occupational environments and adverse health effects. Recent research does not provide evidence to alter this conclusion.

AC audible noise

Manitoba's Provincial Guidelines specify maximum desirable 1-hour equivalent noise levels for residential and commercial areas of 55 dBA and 45 dBA, for day-time and night-time periods, respectively. The median AN levels, generated by corona on the proposed 230-kV and 138-kV transmission lines at the edge of the ROW, are estimated to be 12.1 dBA during fair weather and 37.1 dBA during foul weather, well below the Province's AN guidelines.

AC radio noise

The Industry Canada standard for RN for a 230-kV transmission lines is 53 dBμV/m at 15 m from the nearest conductor that would be measured by a CISPR-type measuring instrument according to CSA Standard C108.1.1-1977 (Industry Canada, 2001). The calculated levels of RN at 15 m from the outer conductor of the Henday to Keewatinoow K64H line is 51.6 dBμV/m; at 15 m from the outermost conductor of the 138-kV circuit (KN36), on the opposite side of the Corridor, the calculated RN level is 44.4 dBμV/m. Thus, the anticipated levels of RN associated with the operation of proposed 230-kV and 138-kV lines on this corridor are calculated to be below the Industry Canada standard.

Conclusions

Based on the modeling of the AC Northern collector and construction power transmission lines, the following conclusions pertain to these lines:

- The levels of EMF, AN, and RN of the proposed 230-kV and 138-kV transmission lines that will provide power to Bipole III from existing hydro-generating sources are all below provincial, national, and international guidelines.

- Further, the conclusions of these scientific agencies have been generally consistent. Overall, they concluded that the research does not show that electric or magnetic fields are a known or likely cause of any disease, including cancer. They also concluded that some statistical data suggests a relationship between childhood leukemia and rare exposure to high magnetic field levels, although the uncertainty associated with these findings and the lack of support from experimental studies does not support a true relationship. (Refer to Appendix B for a more detailed summary).

- Although there are no residential areas close to the Northern Collector line, nevertheless, an optimized phasing for the lines was proposed that will minimize magnetic field levels outside the right-of-way. This no-cost action is consistent with the recommendations of the World Health Organization (WHO, 2007).

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Appendix A

Input data for AC EMF, AN, and RN modeling of the Corridor

Table A-1. Conductor types

Circuit	Voltage (kV)	Conductor type	Conductor diameter (mm)	Number of conductors	Conductor spacing (mm)	SW type	SW diameter (mm)
L61K	230	ACSR Drake	28.1	2	457.2	Steel Strand	9
K61H	230	ACSR Falcon	39.2	1	0	Steel Strand	9
K62H	230	ACSR Falcon	39.2	1	0	Steel Strand	9
K63H	230	ACSR Falcon	39.2	1	0	Steel Strand	9
K64H	230	ACSR Falcon	39.2	1	0	Steel Strand	9
KN36	138	ACSR Oriole	18.8	1	0	Galvanized Steel	9

Table A-2. Conductor locations (horizontal "x" locations measured from the west/left ROW edge)

	Conductor at mid-span [m]						Shield Wire at mid-span [m]			
	A		B		C		1		2	
Circuit	X	Y	X	Y	X	Y	X	Y	X	Y
L61K	136.7	11.1	130.0	11.1	123.3	11.1	126.9	21.9	133.1	21.9
K61H	223.3	9.6	230.0	9.6	236.7	9.6	226.9	21.9	233.1	21.9
K62H	173.3	9.6	180.0	9.6	186.7	9.6	176.9	21.9	183.1	21.9
K63H	73.3	9.6	80.0	9.6	86.7	9.6	76.9	21.9	83.1	21.9
K64H	36.7	9.6	30.0	9.6	23.3	9.6	26.9	21.9	33.1	21.9
KN36	286.7	9.1	280.0	9.1	273.3	9.1	276.9	23.4	283.1	23.4

Table A-3. Loading conditions with Keeyask and the Keewatinoow converter station operating

	Bipole III 2000 MW and 2500 MW, no outages, Average			Bipole III 2000MW and 2500 MW, no outages, Peak			Bipole III 2000MW, HVDC outages, Peak			Bipole III 2500MW, HVDC outages, Peak		
Circuit	MW	MVar	Amps	MW	MVar	Amps	MW	MVar	Amps	MW	MVar	Amps
L61K	154.77	13.40	389.96	231.00	20.00	582.03	288.00	37.00	728.88	469.00	61.00	1,187.21
K61H	58.96	4.02	148.35	88.00	6.00	221.41	117.00	11.00	294.99	280.00	16.00	704.01
K62H	58.96	4.02	148.35	88.00	6.00	221.41	117.00	11.00	294.99	280.00	16.00	704.01
K63H	58.96	4.02	148.35	88.00	6.00	221.41	117.00	11.00	294.99	280.00	16.00	704.01
K64H	58.96	4.02	148.35	88.00	6.00	221.41	117.00	11.00	294.99	280.00	16.00	704.01
KN36	29.93	2.04	125.51	29.93	2.04	125.51	29.93	2.04	125.51	29.93	2.04	125.51

Table A-4. Loading conditions without new generation

Circuit	Bipole III 2,000 MW, no outages, Average			Bipole III 2,000 MW, no outages, Peak			Bipole III 2,500 MW, no outages, Average			Bipole III 2,500 MW, no outages, Peak			Bipole III 2,000 MW, DC outages, Peak			Bipole III 2,500 MW, DCDC outages, Peak		
	MW	MVar	Amps	MW	MVar	Amps	MW	MVar	Amps	MW	MVar	Amps	MW	MVar	Amps	MW	MVar	Amps
L61K	211.05	27.47	534.25	315.00	41.00	797.39	210.38	4.69	528.23	314.00	7.00	788.40	456.00	138.00	1195.92	490.00	169.00	1,301.11
K61H	149.41	10.05	375.90	223.00	15.00	561.04	149.41	9.38	375.79	223.00	14.00	560.88	391.00	149.00	1050.35	510.00	199.00	1,374.22
K62H	149.41	10.05	375.90	223.00	15.00	561.04	149.41	9.38	375.79	223.00	14.00	560.88	391.00	149.00	1050.35	510.00	199.00	1,374.22
K63H	149.41	10.05	375.90	223.00	15.00	561.04	149.41	9.38	375.79	223.00	14.00	560.88	391.00	149.00	1050.35	510.00	199.00	1,374.22
K64H	149.41	10.05	375.90	223.00	15.00	561.04	149.41	9.38	375.79	223.00	14.00	560.88	391.00	149.00	1050.35	510.00	199.00	1,374.22
KN36	29.93	2.04	125.51	29.93	2.04	125.51	29.93	2.04	125.51	29.93	2.04	125.51	29.93	2.04	125.51	29.93	2.04	125.51

Appendix B

Exponent's Report on EMF and Health

Exponent®

Health Sciences Group

Research on Extremely Low Frequency Electric and Magnetic Fields from Alternating Current Transmission Lines—Summary Evaluation of the Evidence

Research on Extremely Low Frequency Electric and Magnetic Fields from Alternating Current Transmission Lines—Summary Evaluation of the Evidence

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February 2011

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Notice

This report summarizes work performed to-date and presents the findings resulting from that work. The findings presented herein are made to a reasonable degree of 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

Contents

Executive Summary

Over the past 30 years, an extensive body of research has developed that addresses extremely low frequency electric and magnetic fields (ELF EMF) and health. As described in Section 1 of this report, ELF EMF is associated with anything that generates, transmits, or uses electricity, so it is a ubiquitous exposure in all technologically advanced societies. As such, questions about whether such exposure could affect our health were raised in the late 1970s, prompted by epidemiology research that studied the relationship of cancer in children with potential exposure to ELF EMF from nearby power lines.[2] Since that time, researchers from many different scientific disciplines have investigated this question and conducted thousands of epidemiology and laboratory studies related to the potential effects of ELF EMF, including studies of cancer, reproductive effects, and neurological effects, among other outcomes.

The current consensus among the numerous national and international scientific agencies that have reviewed this extensive body of research (including the World Health Organization, the International Agency for Research on Cancer, the National Institute of Environmental Health Sciences, the Health Protection Agency of Great Britain, and the Federal-Provincial-Territorial Radiation Protection Committee of Canada) is that there is no known relationship between exposure to ELF EMF at the levels generally found in residential and occupational environments and adverse health effects. Recent research does not provide evidence to alter this conclusion.

Despite the conclusions reached based upon this research, the public frequently expresses concern about ELF EMF, often in the context of proposed new transmission lines. One question that often arises is why scientists continue research if there is strong evidence of no effect. Scientific research and the publication of study results is a constantly evolving process. The fact that scientists have failed to identify any adverse effects of ELF EMF after extensive testing increases the certainty that there are not any risks, or that any possible risk associated with exposure is small. The nature of scientific investigation dictates that the possibility that ELF EMF (or any other exposure in our environment) might have some adverse effect can never be completely ruled out because it is impossible to prove the absence of an effect. Given the

[2] Wertheimer N. and Leeper E. Electrical wiring configuration and childhood cancer. Am J Epidemiol 109:273-284, 1979.

amount and quality of research that has been conducted thus far, however, the opinion of scientific organizations is strong that there is not a cause-and-effect relationship.

A conclusion about any risk associated with ELF EMF is only reached by an unbiased evaluation of the entire research database using established scientific methods. The scientific research process and the scientific organizations that have carried out evaluations of research on ELF EMF are highlighted in Sections 2 and 3. In Section 4, the current consensus these organizations related to particular health outcomes, including childhood cancers (leukemia and brain cancer), adult cancers (brain, lymphohematopoietic, and breast), neurodegenerative diseases, and reproductive effects, is summarized. Finally, the standards and guidelines that have been established, the precautionary measures that are recommended, and a brief review of some additional research topics are covered in Sections 5, 6, and 7, respectively.

1. Introduction to Electric and Magnetic Fields

The term "field" describes the space surrounding a particular object where the properties of that object exert an influence—a temperature field, for example, surrounds warm objects because of the radiating nature of heat. Electric fields and magnetic fields (EMF) surround both man-made and natural sources.[3] Man-made EMF surrounds objects that generate, transmit, or use electricity such as power stations, transmission lines, distribution lines, the wiring in our homes and offices, and the appliances and myriad of electronic devices used in everyday life. EMF from these sources changes direction and intensity 60 times, or cycles, per second—a frequency of 60 Hertz (Hz)—is, therefore, referred to as alternating current (AC) power. Research on ELF EMF has focused primarily on AC power.[4] Fields generated at these extremely low frequencies (i.e., 30 – 300 Hz) differ significantly from the natural static fields (0 Hz) of the earth and fields at higher frequencies characteristic of radio and television signals, microwave ovens, cellular phones, and radar, all of which can have frequencies up to billions of Hz.

Electric fields are the result of voltages applied to electrical conductors and equipment. The electric field is expressed in measurement units of volts per meter (V/m) or kilovolts per meter (kV/m), where 1 kV/m is equal to 1,000 V/m. Most objects including fences, shrubbery, and buildings easily block electric fields. Therefore, certain appliances within homes and the workplace are the major sources of electric fields indoors, while power lines are the major sources of electric fields outdoors (Figure 1, lower panel).

Magnetic fields are produced by the flow of electric currents. Unlike electric fields, most materials do not readily block magnetic fields. The strength of magnetic fields is commonly expressed as magnetic flux density in units of gauss (G) or milligauss (mG), where 1 G is equal

3 Natural sources of electric fields occur in the earth's atmosphere, most commonly experienced during thunderstorms. Although it differs from the magnetic fields generated by AC electricity because it is static, the earth's geomagnetic field is the dominant natural source of magnetic fields. The intensity of the geomagnetic field varies with latitude; the lowest values (~ 300 mG) are measured near the equator and higher values (up to ~700 mG) are measured near the north and south poles.

4 Throughout the world, AC transmission is a more common means of power distribution than direct current (DC) or static transmission, which is used primarily for transmission of power across very long distances. For this reason, research has focused on the effects of AC EMF.

to 1,000 mG.[5] The strongest sources of AC magnetic fields that we encounter indoors are electrical appliances (Figure 1, upper panel).

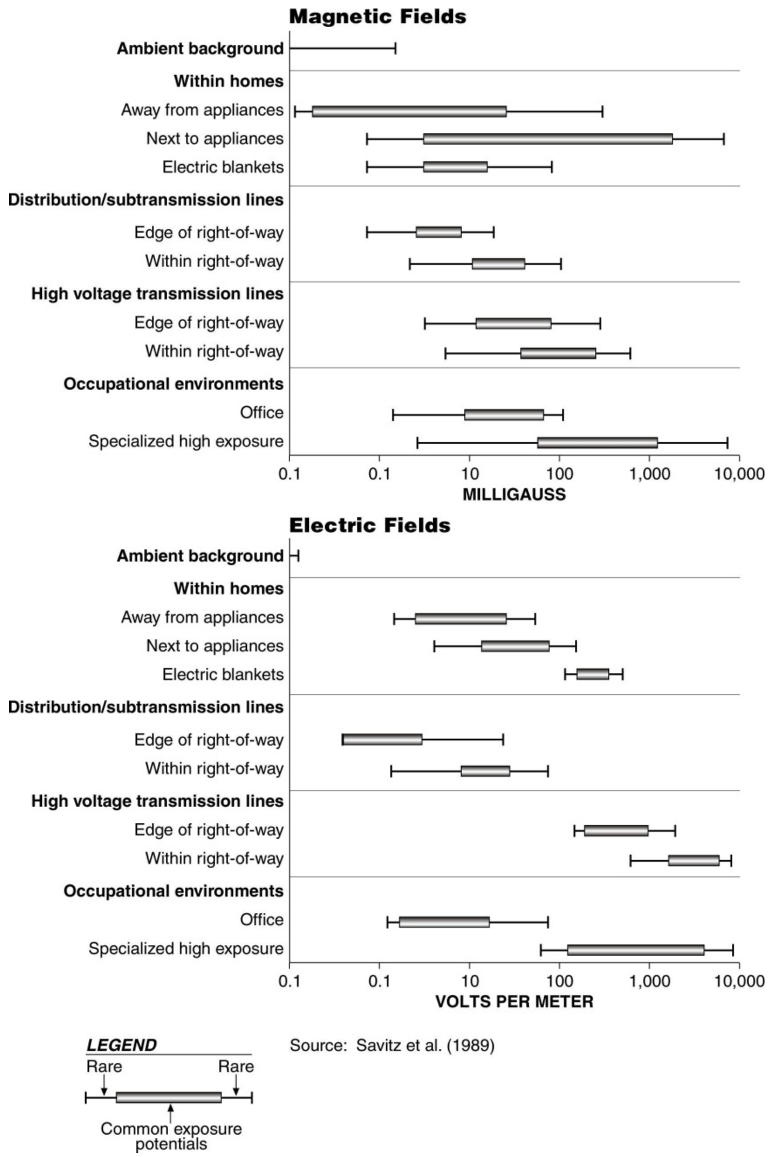

Figure 7. Typical exposure potentials to electric and magnetic fields in common environments.

The level of EMF produced by these sources depends on their structure, location, and various operating characteristics; the magnetic field level produced by a particular power line, for

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5 Scientists more commonly refer to magnetic flux density at lower levels in units of microtesla (µT). Magnetic flux density in milligauss units can be converted to µT by dividing by 10, i.e., 1 mG = 0.1 µT.

example, depends on the configuration of its conductors, their height from the ground, and the amount of current running through the line, among other things.

The strength of both electric fields and magnetic fields decreases with distance from the source. Thus, personal exposure to EMF from a particular object depends largely on a person's distance from that object. While appliances tend to produce the highest levels of magnetic fields in our home and work environments, the magnetic fields from appliances drop off more quickly with distance than other EMF sources.[6]

Every individual has an "average" EMF exposure level that is defined by the environments where they spend time, the sources encountered in those locations, and the duration of exposure to these sources. If any of these variables change, the person's average exposure may be altered. Occupation as a welder or railway worker, for example, would elevate a person's average EMF exposure for the duration of that employment; or, if a person lived in a home with faulty wiring, his or her average EMF exposure may be elevated during that period. Background levels of magnetic fields (estimated from an average of measurements taken throughout a typical home away from appliances) range from 1-2 mG, while background levels of electric fields range from 0.01-0.02 kV/m; however, in proximity to appliances, magnetic field levels can be hundreds of times higher and electric field levels tens of times higher, as illustrated in Figure 1 (Savitz et al., 1989; WHO, 2007). The ubiquitous nature of EMF and variability in average exposure levels make it difficult to quantify levels of exposure for research studies. As a result, the major limitation of health studies of EMF is the methods used for estimating exposure.

Data from Canada show that persons are exposed to daily average levels of approximately 1 mG (Armstrong et al., 2001). The average magnetic-field exposures of American children are similar (Zaffanella, 1998). Figure 2 below displays data from measurements taken by a gaussmeter worn by a person for a 48-hour period while conducting ordinary activities at home, at work, and in between (i.e., driving and riding the train). These measurements illustrate the continuous but varying levels of magnetic fields that most people encounter each day. Even though high levels

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6 Fields near appliances vary over a wide range, from a fraction of 1 mG to 1,000 mG or more. Gauger (1985) reported the maximum AC magnetic field at 3 centimeters from a sampling of appliances as 3,000 mG (can opener), 2,000 mG (hair dryer), 5 mG (oven), and 0.7 mG (refrigerator).

of exposure were common and the highest level reached 168 mG, such high exposures were brief. Average exposure over these two days was just a fraction over 1 mG.

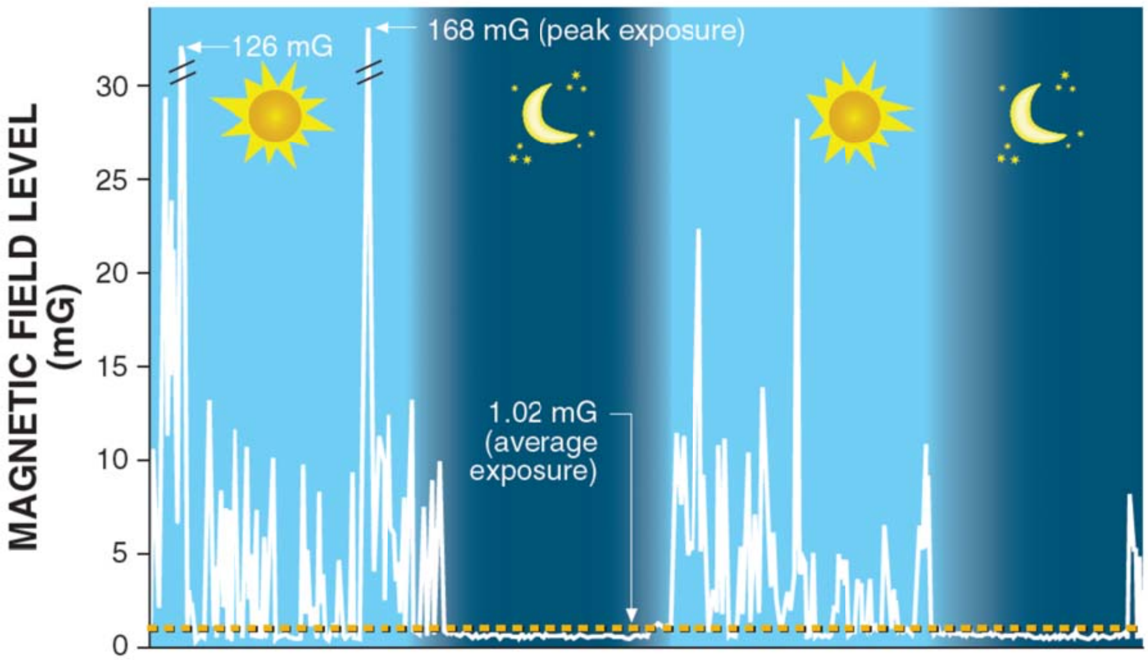

Figure 8. Magnetic field exposure over the course of a 48-hour period.

Source: Exponent (2007)

2. Scientific Research Process

Scientific inquiry is not simply a collection of facts – it is a systematic and unbiased reasoning process used to arrive at accurate and balanced conclusions. The scientific process must, therefore, be conducted in a manner to ensure that conclusions are supported by the research. Many misconceptions in human reasoning occur, for example, when casual observations are made about a particular experience (for example, if a person develops a headache after eating a particular food, he or she may ascribe the headache to the food). Proximity of events or conditions, however, does not guarantee a causal relationship. The same mistake can occur when conclusions are based on the results of single studies. Scientists use systematic methods to evaluate observations and assess the potential impact of a specific agent on human health.

The scientific process involves looking at *all* the evidence on a particular issue in a systematic and thorough manner, an evaluation that is often referred to as a weight-of-evidence review. This process is designed to ensure that more weight is given to studies of better quality and that studies with a given result are not selected from the available evidence to advocate or suppress a preconceived hypothesis. Conclusions about health risks cannot be drawn from single studies because every study has limitations in one way or another. A weight-of-evidence review is based on a comprehensive assessment of the three main types of scientific research (Figure 3): epidemiology studies of humans; experimental studies in animals (*in vivo*); and experimental studies in isolated cells and tissues (*in vitro*).

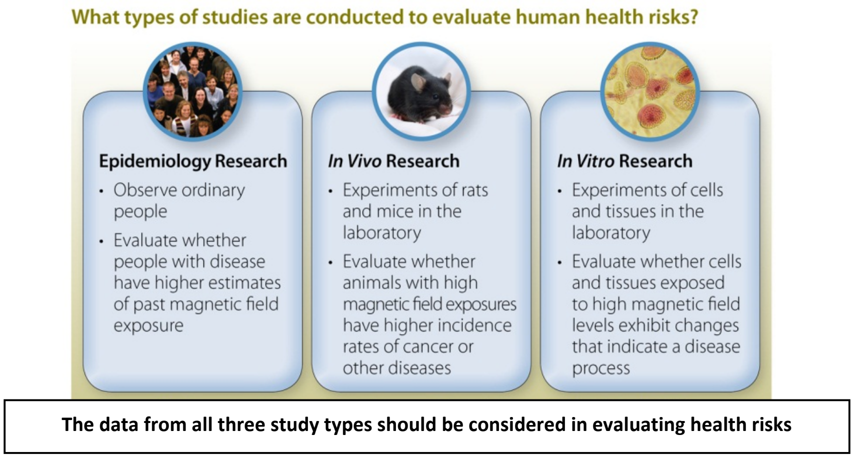

Figure 9. Study types included in a weight-of-evidence review

A weight-of-evidence review first evaluates individual studies in terms of their strengths and weaknesses and then evaluates all of the studies together, taking the appropriate pieces of evidence from each study to form a conclusion. In this process, the information provided by epidemiology and *in vivo* studies is complementary. Epidemiology studies are limited by the lack of control they have over their study participants, but provide information directly relevant to the species of interest; the results from *in vivo* studies, while often more accurate because of the experimental nature of the study, need to be extrapolated to what would be expected in humans. Thus, the overall patterns of results from epidemiology **and** *in vivo* studies are considered because epidemiology studies address the limitations of *in vivo* studies and vice versa.[7]

Each study contributes a different type and weight of evidence due to the inherent qualities of its study design, the methods used in collecting and analyzing the data, and any biases that may have arisen during the course of the study. A high-quality epidemiology study, for example, would consist of a large cohort of a highly-exposed population with follow-up of all its study participants over a long period of time with detailed measurements of exposure for each study participant during the relevant periods of exposure. This study design is expensive and time-

[7] The findings of *in vitro* studies are used by health and regulatory agencies to help them interpret the results of *in vivo* studies, but *in vitro* studies may not be representative of the response to the agent of interest. These agencies, therefore, do not directly rely on *in vitro* studies to make policy decisions.

consuming; thus, other study types (e.g., the case-control design) and dosimetric methods (e.g., job-exposure matrices) are used with a full understanding of their limitations.

The main result of an epidemiology study is the statistical association measured between the exposure and disease of interest. When evaluating any study, it is important to consider that its results do not represent the real relationship between an exposure and a disease; rather, the results represent some estimation of the relationship in a single population, which is limited by the study's methods and, in the case of epidemiology studies, the unpredictable behavior of the study's participants. In fact, much of epidemiologic analysis involves the interpretation of how outside factors could have affected the study's statistical findings.

Statistical associations in cohort studies are summarized by a computed relative risk, which is a ratio of the risk of the disease in the exposed group to the ratio of the risk in the unexposed group. A value greater than 1.0 indicates a positive association and a possible risk associated with exposure. Case-control studies estimate relative risks with an odds ratio, which is a ratio of the odds of exposure among persons with a disease (i.e., cases) to the odds of exposure among a similar population without disease (i.e., controls).

Three factors are always considered when evaluating the weight assigned to any statistical association:

1. ***Chance***. A statistical association may simply be due to a chance occurrence. Statistical tests are performed to evaluate whether chance is a likely explanation.

2. ***Bias.*** Bias is any systematic error in the design, implementation, or analysis of a study that results in a mistaken estimate of an exposure's effect on the risk of disease. Bias can occur, for example, if a study compares disease rates of exposed and unexposed groups comprised of persons in different age groups.

3. ***Confounding.*** A confounder is something that is related to both the disease under study and the exposure of interest such that one cannot be sure what causes the observed association—the confounder or the exposure of interest. With regard to epidemiology studies of EMF from distribution lines and childhood cancer, some

scientists have investigated whether the association is confounded by exposures to emissions from vehicles on adjacent roadways.

Scientific diligence and care must be taken in the design and analysis of studies to evaluate the role of chance and minimize bias and confounding so these factors do not distort the study's findings.

Scientific panels often classify epidemiologic data as providing sufficient, limited, inadequate evidence in support of carcinogenicity (i.e., the ability of an agent to cause cancer), or evidence suggesting a lack of carcinogenicity, using the standardized classification process established by the International Agency for Research on Cancer (IARC). For the evidence to be considered sufficient, the role of chance, bias, and confounding on the observed association must be ruled out with "reasonable confidence." If the role these factors may play in the calculated statistical association cannot be ruled out with reasonable confidence, then the data is classified as providing limited evidence. Inadequate evidence describes a data set that lacks quality, consistency, or power for conclusions regarding causality to be drawn. This classification system is used for both epidemiology studies and *in vivo* studies and is used to provide summary descriptions of an exposure's potential to cause cancer – known carcinogens, probable carcinogens, possible carcinogens, not classifiable, and probably not a carcinogen (as illustrated in Figure 4).

	Epidemiology Studies				Animal Studies			
	Sufficient evidence	Limited evidence	Inadequate evidence	Evidence suggesting lack of carcinogenicity	Sufficient evidence	Limited evidence	Inadequate evidence	Evidence suggesting lack of carcinogenicity
Known Carcinogen	✓							
Probable Carcinogen		✓			✓			
Possible Carcinogen		✓				✓	✓	
Not Classifiable			✓			✓	✓	
Probably not a Carcinogen				✓				✓

Sufficient evidence in epidemiology studies—A positive association is observed between the exposure and cancer in studies, in which chance, bias and confounding were ruled out with "reasonable confidence."

Limited evidence in epidemiology studies—A positive association has been observed between the exposure and cancer for which a causal interpretation is considered to be credible, but chance, bias or confounding could not be ruled out with "reasonable confidence."

Inadequate evidence in epidemiology studies—The available studies are of insufficient quality, consistency or statistical power to permit a conclusion regarding the presence or absence of a causal association between exposure and cancer, or no data on cancer in humans are available.

Evidence suggesting a lack of carcinogenicity in epidemiology studies—There are several adequate studies covering the full range of levels of exposure that humans are known to encounter, which are mutually consistent in not showing a positive association between exposure to the agent and any studied cancer at any observed level of exposure. The results from these studies alone or combined should have narrow confidence intervals with an upper limit close to the null value (e.g. a relative risk of 1.0). Bias and confounding should be ruled out with reasonable confidence, and the studies should have an adequate length of follow-up.

Sufficient evidence in animal studies—An increased incidence of malignant neoplasms is observed in (a) two or more species of animals or (b) two or more independent studies in one species carried out at different times or indifferent laboratories or under different protocols. An increased incidence of tumors in both sexes of a single species in a well-conducted study, ideally conducted under Good Laboratory Practices, can also provide sufficient evidence.

Limited evidence in animal studies—The data suggest a carcinogenic effect but are limited for making a definitive evaluation, e.g. (a) the evidence of carcinogenicity is restricted to a single experiment; (b) there are unresolved questions regarding the adequacy of the design, conduct or interpretation of the studies; etc.

Inadequate evidence in animal studies—The studies cannot be interpreted as showing either the presence or absence of a carcinogenic effect because of major qualitative or quantitative limitations, or no data on cancer in experimental animals are available

Evidence suggesting a lack of carcinogenicity in animal studies—Adequate studies involving at least two species are available which show that, within the limits of the tests used, the agent is not carcinogenic.

Figure 10. IARC method for classifying exposures according to carcinogenicity

3. Scientific Reviews of ELF EMF

Multidisciplinary scientific panels of both international and national scientific and governmental agencies regularly conduct weight-of-evidence reviews about possible health risks—it is these evaluations and the conclusions stemming from them that guide research priorities and help set standards and guidelines to reduce potential exposure risks. Numerous weight-of-evidence reviews of the research literature on ELF EMF and possible adverse health effects have been conducted by and national scientific and governmental agencies. The major agencies that have reviewed this topic are listed below in Table 1, with their most recent weigh-of-evidence review indicated.

Table 5. Weight-of-evidence and other major reviews, 1998 - 2010

Year	Agency	Publication
1998	National Institute for Environmental Health Sciences (NIEHS)	Assessment of health effects from exposure to power-line frequency electric and magnetic fields: working group report
1998, updated in 2005	Federal-Provincial-Territorial Radiation Protection Committee (FPTRPC)	Health effects and exposure guidelines related to extremely low frequency electric and magnetic fields—an overview
2002	International Agency for Research on Cancer (IARC)	IARC monographs on the evaluation of carcinogenic risks to humans. Volume 80: Static and extremely low-frequency (ELF) electric and magnetic fields
2004	National Radiological Protection Board of Great Britain (NRPB) Currently known as the Health Protection Agency [HPA] of Great Britain	Review of the scientific evidence for limiting exposure to electromagnetic fields (0-300 GHz). Volume 15, No. 3
2007	World Health Organization (WHO)	Environmental Health Criteria 238: Extremely low frequency (ELF) Fields
2008	Swedish Radiation Protection Agency (SSI)	Fifth Annual report from SSI's Independent Expert Group on electromagnetic fields, 2007: Recent research on EMF and health risks
2009	Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR)	Health effects of exposure to EMF
2010	ICNIRP	ICNIRP Statement—Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 KHz)

None of these agencies has concluded that exposure to ELF EMF is a demonstrated cause of any long-term adverse health effect. Section 4 describes the current scientific evidence with regard to specific health outcomes. The evidence in support of a causal relationship is weak because it is founded largely, if not entirely, on *some* epidemiology studies that reported statistical associations between higher estimated average magnetic field exposure and a disease. Overall, the *in vivo* studies did not report an increase in cancer among animals exposed to high levels of electric or magnetic fields, and *in vitro* studies have not confirmed a mechanism that would explain how electric or magnetic fields could initiate disease.

Most notably, a weak statistical association was reported between childhood leukemia and estimates of long-term exposure to high average magnetic field levels (3-4 mG). The overall body of research, however, does not indicate that this association, or any other, is causal in nature. Weaknesses in the epidemiology studies of childhood leukemia limit the significance of their findings; specifically, scientists have not been able to rule out the possibility that confounding or bias contributes to the statistical association between magnetic fields and childhood leukemia reported in these studies. Furthermore, findings from *in vivo* and *in vitro* studies do not support a causal relationship.

The only studies that can be said to confirm a relationship between electric fields or magnetic fields and an adverse biological or health effect are those in which very high levels of exposure to these fields produce currents and fields in the body, which can result in a shock-like effect. The levels at which these short-term effects occur are very high and may not even be reached in high exposure occupational environments. Several organizations have recommended exposure guidelines to protect against their occurrence. These guidelines are summarized in Section 5.

The conclusions of the most extensive of these scientific reviews—the WHO review—, which were published in 2007, are summarized in Appendix 1. Several scientific organizations have recently released reports or statements of note related to ELF EMF. When ICNIRP prepared revised guidelines for ELF EMF exposure, which were released in December 2010, they also reviewed the evidence related to long-term health effects, and they concluded the following:

> *The literature on chronic effects of ELF fields has been evaluated in detail by individual scientists and scientific panels. WHO's cancer research institute, IARC (International Agency for Research on Cancer) evaluated ELF magnetic fields in 2002 and classified them in category 2B, which translates to "possibly carcinogenic to humans." The basis for this classification was the epidemiologic results on childhood leukemia. It is*

> *the view of ICNIRP that the currently existing scientific evidence that prolonged exposure to ELF magnetic fields is causally related with an increased risk of childhood leukemia is too weak to form the basis for exposure guidelines* (ICNIRP 2010, p. 824).

The FPTRPC of Canada released a statement in November 2008 that concluded the following with respect to EMF and health:

> *In summary, it is the opinion of the Federal-Provincial-Territorial Radiation Protection Committee that there is insufficient scientific evidence showing exposure to EMFs from power lines can cause adverse health effects such as cancer.*

This conclusion is consistent with statements by Health Canada in their publication "*It's Your Health—Electric and Magnetic Fields at Extremely Low Frequencies*," which were updated in January 2010. Specifically, they state, "In summary, when all of the studies are evaluated together, the evidence suggesting that EMFs may contribute to an increased risk of cancer is very weak." This publication can be found on Health Canada's website and is also included in Appendix 2.[8]

The following section reviews the current consensus of these organizations related to particular health outcomes, including childhood cancers (leukemia and brain cancer), adult cancers (brain, lymphohematopoietic, and breast), neurodegenerative diseases, and reproductive effects. For reference Appendix 3 provides a listing of epidemiology studies published since the time of the WHO 2007 review.

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[8] http://www.hc-sc.gc.ca/hl-vs/iyh-vsv/environ/magnet-eng.php

4. Current Consensus on Specific Health Outcomes

Childhood leukemia

The incidence rate of leukemia in children is approximately 3 per 100,000 per year, making it a relatively rare cancer, and in the vast majority of cases, the cause is unknown. The only identified causes of childhood leukemia include certain genetic diseases, chemotherapeutic agents, and ionizing radiation from sources such as maternal x-rays during pregnancy, but these account for only a very small percentage of cases. Since so little is known about the cause of this disease, many exposures have been investigated, including infectious agents and environmental exposures such as pesticides, solvents, pollution, and magnetic fields, but no clear patterns have emerged. Suggestive data exists for the role of infections in promoting leukemia in already susceptible children, but the research is inadequate so conclusions about this possible cause are not definitive.

Since 1979, epidemiology studies conducted in the United States, Canada, Europe, New Zealand, and Asia have evaluated the relationship between childhood leukemia and some proxy of magnetic field exposure. Independently, these studies did not show a clearly consistent association between magnetic fields and childhood leukemia. The largest and most methodologically sound case-control studies in this group that directly estimated magnetic field exposure through long-term personal measurements were conducted by Linet et al. (1997) in the United States, McBride et al. (1999) in Canada, and the United Kingdom Childhood Cancer Study Investigators in the UK (UKCCS, 1999, 2000). None of the investigator who performed these studies concluded that their data showed a causal relationship between childhood leukemia and magnetic fields.

A 2-fold statistically-significant association was observed between magnetic fields and childhood leukemia when two independent pooled analyses combined the data from most of the case-control studies published prior to 2000; this association was only observed at rare average magnetic field exposure levels above 3-4 mG (Ahlbom et al., 2000; Greenland et al., 2000).[9] As a result of the findings by Ahlbom et al. and Greenland et al., the IARC and WHO concluded that there is a statistical association between magnetic fields and childhood leukemia.

Researchers have not concluded, however, that the weak association between childhood leukemia and magnetic fields is causal in nature because the studies are of insufficient quality to rule out the role that chance, bias (e.g., exposure misclassification), and confounding may have on the observed statistical association with "reasonable confidence." As described in Section 2, statistical associations are a measure of how disease and exposure estimates vary together in a specific population, but do not indicate that two factors are causally related. Conclusions about causality are made only when strong epidemiologic data are consistent with the data from *in vivo* research, and the studies that present such data have confidently ruled out that chance, bias, or confounding played a role in the statistical association. In their 2007 report, the WHO concluded that, while chance is an unlikely explanation, bias arising from uncertainties in exposure (i.e., misclassification) and non-participation of highly-exposed controls (i.e., selection bias) is likely.

Although the WHO report (2007) identified confounding as an unlikely explanation for the statistical association, the reviewers could not rule out its influence because so little is known about the causes of childhood leukemia. Since transmission line right-of-ways are often built along highways, children who live near power lines may also be likely to live near highways. If pollutants from traffic emissions were a cause of childhood leukemia, the association between residential distance to power lines and childhood leukemia could be the result of pollutants from traffic, not magnetic fields from transmission lines. While this is a plausible theory, the research on traffic emissions and childhood leukemia is inconsistent and weak.

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9 Pooled and meta-analyses combine data from original studies to calculate a summary estimate of the association. Pooled analyses combine the actual raw data, while meta-analyses combine the measures of association. The results indicate that children with leukemia were about two times more likely to have had estimated average magnetic field exposures above 3-4 mG.

Approximately 18 studies related to childhood leukemia have been published between 2006 and 2010, but these have failed to explain the statistical association between estimates of high average exposure to magnetic fields (i.e., greater than 3-4 mG) and childhood leukemia.[10] Most notably, Kheifets et al. (2010) conducted a pooled analysis of studies published between 2000 and 2010 that was intended to mirror the earlier pooled analyses of studies published between 1974 and 1999 (Ahlbom et al., 2000; Greenland et al., 2000). Kheifets et al. identified six studies for the main analysis that met their inclusion criteria (i.e., population-based studies of childhood leukemia that measured or calculated magnetic fields inside a home). A large number of cases were identified by Kheifets et al. (10,865), but a relatively small number of cases (23) were classified in the highest exposure category (>3 mG). A positive association was reported (OR=1.44), but it was weaker than the previous pooled estimates and not statistically significant (95% CI=0.88–2.36); a non-significant dose-response relationship was described.

No studies have replicated the statistical association between childhood leukemia and average *personal* exposure greater than 3-4 mG, although recent studies have reported associations of magnetic fields with poor health outcomes at estimates of elevated magnetic field levels. Specifically, these studies reported that children with leukemia and estimates of elevated average magnetic field exposures had poorer survival rates; children with Down's syndrome and childhood leukemia were more likely to have an estimated magnetic field exposure greater than 6 mG; and children with leukemia and a genetic variation associated with a reduced ability to repair DNA were more likely to live closer to an electrical installation. None of the studies, however, is methodologically strong.

Recent studies have also reported an association between higher calculated magnetic fields from nearby power lines and childhood leukemia. Like the studies reviewed by the WHO, these studies have limitations that preclude any clear interpretation. Furthermore, the studies tested new hypotheses without supporting biological evidence and, therefore, require replication. Thus, reviews of these newer studies by the Swedish Radiation Protection Authority and the Scientific Committee on Emerging and Newly Identified Health Risks have not concluded that they strengthen the weight of evidence for an association of magnetic fields and childhood leukemia (SCENIHR, 2009; SSI, 2007, 2008).

[10] A table of epidemiology studies published after the WHO report is included in Appendix 3.

As suggested by the WHO report, methodological research has recently been conducted to determine the role that confounding or control selection bias may have on the observed association.[11] Findings suggest that control selection bias is operating to some extent. More research is required to further evaluate the role of control selection bias and confounding.

None of these recent studies are sufficiently strong methodologically, nor do the findings display causal patterns (i.e., exposure-response, consistency, and strength) to alter previous conclusions that the epidemiologic evidence related to magnetic fields and childhood leukemia is limited. Chance, confounding, and several sources of bias cannot be ruled out as an explanation for the observed statistical association. The lack of evidence from recent *in vivo* research supports this conclusion.

Childhood brain cancer

Similar to childhood leukemia, the causes of childhood brain cancer are relatively unknown. Only two causes—radiotherapy for the treatment of other cancers and a particular genetic mutation—have been identified. Far fewer studies have been published on magnetic fields and childhood brain cancer than studies on childhood leukemia. The WHO report described the results of these studies as inconsistent and limited by small sample size and recommended that a meta-analysis of the data related to childhood brain cancer and magnetic field exposure be performed.

Five studies have been published on childhood brain cancer and EMF since the time of the WHO report. The meta- and pooled analyses conducted in response to the WHO's recommendation reported a very weak association between estimated average exposures greater than 3-4 mG and childhood brain cancer, although the association was not statistically significant (i.e., not distinguishable from chance). The authors concluded that the analyses provide little evidence for a relationship between magnetic fields and childhood brain cancer. Recent studies on the risk of

[11] Control selection bias refers to a particular type of bias that occurs in case-control studies. If the characteristics of the control group differ from the characteristics of the case group in a way that is related to exposure, the measured statistical association will not represent a true relationship. In the case of magnetic fields and childhood leukemia, researchers are concerned that, because of factors that affect participation in a study, the control group may have a higher socio-economic status than the case group and, as a result, lower magnetic field exposures.

childhood brain cancer related to pre- and post-conception parental ELF EMF exposure do not provide strong evidence of a risk and add little to the existing body of inconsistent literature in this area. Thus, the evidence related to childhood brain cancer and magnetic field exposure remains inadequate.

Adult brain and lymphohematopoietic cancers

The WHO and other agencies previously classified studies of these cancer types as inadequate, weak, and seriously limited by methods used for exposure assessment. Twelve recent studies have reported data on adult leukemia, brain cancer and/or lymphoma. Recent studies have reduced possible exposure misclassification by improving exposure assessment methods and attempted to clarify inconsistencies by updating studies and meta-analyzing data; however, despite these advancements, no consistent association has been observed. A meta-analysis was conducted as recommended in the WHO report, which reported a small and statistically significant increase of leukemia and brain cancer in relation to the highest estimate of magnetic-field exposure in the individual studies (Kheifets et al., 2008). Several findings, however, led the authors to conclude that magnetic field exposure is not likely to be responsible for the observed associations. While an association cannot be *entirely* ruled out because of the remaining deficiencies in exposure assessment methods, the current database of studies provides weak evidence of an association between magnetic fields and adult brain and lymphohematopoietic cancers.[12]

Breast cancer

The WHO concluded that there was strong evidence in support of no relationship between magnetic fields and breast cancer; six recent studies, including one large cohort study, support this conclusion.

[12] A recent consensus statement by the National Cancer Institute's Brain Tumor Epidemiology Consortium confirms this statement. They classified residential power frequency EMF in the category "probably not risk factors" and described the epidemiologic data as "unresolved" (p. 1958, Bondy et al., 2008).

Neurodegenerative diseases

The research on ELF EMF and neurodegenerative diseases such as Alzheimer's disease and amyotrophic lateral sclerosis (ALS), also known as Lou Gehrig's disease, did not begin until around 1995, later than other areas of ELF EMF research. The WHO report stated that there is inadequate data in support of an association between magnetic fields and either of these two diseases. Alzheimer's disease, in particular, presents a unique challenge to epidemiologists because of the nature of the disease. Disease onset is typically late in life and is difficult to define because it is often preceded by a period of dementia, which can be misdiagnosed as other neurodegenerative conditions, such as cerebrovascular disease. Misclassification of disease is, therefore, common and the since the disease may be present well before symptoms appear, the etiologically relevant time period used to make estimates of exposure may be incorrect.

Six studies have been published since the WHO report was released that addressed magnetic field exposure and neurodegenerative diseases. While most recent studies and a meta-analysis reported an association between occupational magnetic field exposure and Alzheimer's disease or ALS, the studies are weak in design, meaning the data in support of a causal relationship is still limited. The first study that investigated non-occupational exposure was published recently, reporting that persons living close to high-voltage transmission lines were more likely to have died from Alzheimer's disease than persons living at a distance from these lines. These findings do not provide strong evidence in support of a relationship between Alzheimer's disease and EMF, however, mainly because distance is not a good proxy for magnetic-field exposure.

The recent epidemiology studies do not alter the conclusion that there is "inadequate" data on Alzheimer's disease and ALS. While a good number of studies have been published since the WHO report, little progress has been made on clarifying these associations. Further research is still required, particularly on electrical occupations and ALS. There is currently no body of *in vivo* research to suggest an effect.

Reproductive and developmental effects

Very little epidemiologic research has been published in this area. The WHO categorized this data as inadequate, stating that there is some evidence in support of peak magnetic-field exposures and miscarriage, but there were methodological issues with this research. The results from two recently published studies support the role of bias in the studies of peak magnetic-field exposure and miscarriage. There continues to be no convincing epidemiologic evidence linking magnetic field exposure to the risk of miscarriage.

5. Standards and Guidelines

Since the scientific organizations that regularly review research on ELF EMF have determined there are no known long-term health effects from exposure, no standards or guidelines limiting exposure to ELF EMF based on long-term health effects have been recommended. Accordingly, there are no national standards in Canada or the United States limiting exposures to ELF EMF based on long-term or other health effects.

Two of the scientific organizations that review the scientific literature on ELF EMF (ICNIRP and the International Commission on Electromagnetic Safety [ICES]) have published guidelines limiting exposure to very high levels of ELF EMF based on the avoidance of immediate short-term health effects, which include biological responses such as perception, annoyance, and the stimulation of nerves and muscles. Following a thorough review of the scientific literature related to short- and long-term adverse effects, the ICNIRP published revised guidelines in December 2010 to replace their 1998 ELF EMF guidelines. The document recommended no change to ICNIRP's assessment of the scientific evidence; as before, research related to long-term health effects does not provide sufficient evidence to warrant a change to the exposure guidelines. ICNIRP did, however, raise the residential screening value for magnetic fields from 833 to 2,000 mG. The occupational screening value of 4,200 mG (ICNIRP, 1998; ICNIRP, 2010) was not changed.

The ICES also recommends limiting exposures at high levels because of the risk of immediate stimulation responses, although their guidelines are set well above ICNIRP's guidelines (ICES, 2002).[13] In almost all cases, transmission lines meet these magnetic-field exposure guidelines, although some appliances do not.

[13] The ICES is "responsible for development of standards for the safe use of electromagnetic energy in the range of 0 Hz to 300 GHz relative to the potential hazards of exposure of humans, volatile materials, and explosive devices to such energy, standards for products that emit electromagnetic energy by design or as a by-product of their operation, and standards for environmental limits."

Table 6. Reference levels for whole body exposure to 60-Hz fields: general public

Organization recommending limit	Magnetic fields	Electric fields
ICNIRP restriction level	2,000 mG	4.2 kV /m
ICES maximum permissible exposure (MPE)	9,040 mG	5 kV/m 10 kV/m[a]

[a] This is an exception within transmission line rights of way (ROW) because people do not spend a substantial amount of time in ROWs and very specific conditions are needed before a response is likely to occur (i.e., a person must be well insulated from ground and must contact a grounded conductor).

6. Precautionary Measures

Public concern about the possible adverse effects of exposure to magnetic fields has been addressed by some agencies, such as the WHO and NIEHS, by recommending measures that utilize the precautionary principle. The precautionary principle is a policy that emerged in Europe in the 1970s to address perceived adverse environmental effects. Under the precautionary principle, measures are taken to reduce exposures that are proportional to the perceived level of risk as identified by standard scientific methods. In the case of ELF EMF, since the data suggesting adverse health effects are weak, precautionary measures have been recommended that are not costly and are easy to implement. For example, moving appliances away from sleeping areas is one no cost way to reduce exposure. The WHO recommended the following precautionary approaches in their 2007 report (p. 372-373):

- Policy-makers should establish guidelines for ELF field exposure for both the general public and workers [related to short-term stimulation effects]. The best source of guidance for both exposure levels and the principles of scientific review are the international guidelines.
- Policy-makers should establish an ELF EMF protection programme that includes measurements of fields from all sources to ensure that the exposure limits are not exceeded either for the general public or workers.
- Provided that the health, social, and economic benefits of electric power are not compromised, implementing very low-cost precautionary procedures to reduce exposures is reasonable and warranted.
- Policy-makers and community planners should implement very low-cost measures when constructing new facilities and designing new equipment including appliances.
- Changes to engineering practice to reduce ELF exposure from equipment or devices should be considered, provided that they yield other additional benefits, such as greater safety, or involve little or no cost.
- When changes to existing ELF sources are contemplated, ELF field reduction should be considered alongside safety, reliability and economic aspects.

- Local authorities should enforce wiring regulations to reduce unintentional ground currents when building new or rewiring existing facilities, while maintaining safety. Proactive measures to identify violations or existing problems in wiring would be expensive and unlikely to be justified.
- National authorities should implement an effective and open communication strategy to enable informed decision-making by all stakeholders; this should include information on how individuals can reduce their own exposure.
- Local authorities should improve planning of ELF EMF-emitting facilities, including better consultation between industry, local government, and citizens when siting major ELF EMF-emitting sources.
- Government and industry should promote research programmes to reduce the uncertainty of the scientific evidence on the health effects of ELF field exposure.

In Canada, the FPTRPC's approach to precautionary measures is similar to the recommendations made by the WHO. The FPTRPC stated, "In the context of power-frequency EMFs, health risks to the public from such exposures have not been established; therefore, it is the opinion of the FPTRPC that any precautionary measures applied to power lines should favour low cost or no cost options."

7. Other Research Topics

High-voltage and ultra-high-voltage transmission lines often traverse farmland, forests, and woodlands that have substantial populations of both domestic and wild animals and a wide variety of crops and plants. Prompted by concerns about the effects of EMF through these areas, research has been conducted since the 1970s on the possible effects of EMF on the health, behavior, and productivity of a number of species, including livestock and a range of wild animals and insects, as well as the possible effects on farm crops and natural flora. The research to date does not suggest that magnetic or electric fields (or any other aspect of high-voltage transmission lines, such as audible noise) result in adverse effects on the health, behavior, or productivity of fauna, including livestock such as dairy cows, sheep, pigs, and a variety of other species including small mammals, deer, elk, birds, and bees. Studies were also conducted to evaluate whether EMF could affect crops or plants, but did not suggest any adverse effects on growth or viability.

Another area of concern that has been raised in relation to EMF exposure is the effects of these fields on pacemakers or implanted cardiac devices (ICDs). The heart's rhythm is controlled naturally by electrical signals. When there is a disturbance to this rhythm, a pacemaker or ICD is implanted to restore normal cardiac function. Since the sensing system of these devices is naturally responsive to the heart's electrical signal, other electrical signals can interfere with the normal functioning of pacemakers and ICDs, a phenomenon called electromagnetic interference (EMI). Potential sources of EMI include cellular telephones, anti-theft devices in stores, MRI machines, slot machines, and certain medical procedures (e.g., radiation therapy, electrocautery, and defibrillation). Experimental tests have shown sometimes subtle effects of strong electric fields on pacemaker operation, but no case reports of interference with patients' pacemakers by electric or magnetic fields associated with transmission lines have been reported in the literature. Transmission line magnetic fields are generally too weak to affect pacemakers, and electric field strength decreases with distance and is shielded by trees, buildings, vehicles, fences, etc. Most devices are now constructed with features that prevent interference.

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Appendix 1

Conclusions of the WHO's Environmental Health Criteria 238

Outcome	WHO conclusion or recommendation in 2007
Overall conclusions	"New human, animal, and in vitro studies published since the 2002 IARC Monograph, 2002 [*sic*] do not change the overall classification of ELF as a possible human carcinogen" (p. 347). "Acute biological effects [i.e., short-term, transient health effects such as a small shock] have been established for exposure to ELF electric and magnetic fields in the frequency range up to 100 kHz that may have adverse consequences on health. Therefore, exposure limits are needed. International guidelines exist that have addressed this issue. Compliance with these guidelines provides adequate protection. Consistent epidemiological evidence suggests that chronic low-intensity ELF magnetic field exposure is associated with an increased risk of childhood leukaemia. However, the evidence for a causal relationship is limited, therefore exposure limits based upon epidemiological evidence are not recommended, but some precautionary measures are warranted" (p. 355-6).
Childhood leukemia	"Consistent epidemiological evidence suggests that chronic low intensity ELF magnetic field exposure is associated with an increased risk of childhood leukaemia. However, the evidence for a causal relationship is limited, therefore exposure estimates based upon epidemiological evidence are not recommended, but some precautionary measures are warranted" (p. 355-6).
Childhood brain cancer	The WHO described the data related to childhood brain cancer as inadequate. They stated, "As with childhood leukaemia, a pooled analysis of childhood brain cancer studies should be very informative and is therefore recommended. A pooled analysis of this kind can inexpensively provide a greater and improved insight into the existing data, including the possibility of selection bias and, if the studies are sufficiently homogeneous, can offer the best estimate of risk" (p. 18).
Adult leukemia Adult brain cancer	The WHO concluded, "In the case of adult brain cancer and leukaemia, the new studies published after the IARC monograph do not change the conclusion that the overall evidence for an association between ELF [EMF] and the risk of these disease remains inadequate" (p. 307).
Breast cancer	The WHO concluded, "[w]ith these [recent] studies, the evidence for an association between ELF magnetic field exposure and the risk of female breast cancer is weakened considerably and does not support an association of this kind" (p. 9).

Outcome	WHO conclusion or recommendation in 2007
In vivo cancer research	The WHO concluded "[t]here is no evidence that ELF exposure alone causes tumours. The evidence that ELF field exposure can enhance tumour development in combination with carcinogens is inadequate" (p. 10).
Neurodegenerative diseases	"Overall, the evidence for the association between ELF exposure and ALS is considered inadequate. The few studies investigating the association between ELF exposure and Alzheimer's disease are inconsistent. However, the higher quality studies that focused on Alzheimer morbidity rather than mortality do not indicate an association. Altogether, the evidence for an association between ELF exposure and Alzheimer's disease is inadequate" (p. 206).
Reproductive effects	"On the whole, epidemiological studies have not shown an association between adverse human reproductive outcomes and maternal or paternal exposure to ELF fields. There is some evidence for increased risk of miscarriage associated with measured maternal magnetic field exposure, but this evidence is inadequate" (p. 255).

Appendix 2

Health Canada
It's Your Health – Electric and Magnetic Fields at Extremely Low Frequencies

Electric and Magnetic Fields At Extremely Low Frequencies

The Issue

There are concerns that daily exposure to electric and magnetic fields (EMFs) may cause health problems. These concerns are reflected in a number of reports that have attempted to link EMF exposure to a variety of health issues, including childhood cancer.

Background

Electricity delivered through power lines plays a central role in modern society. It is used to light homes, prepare food, run computers and operate other household appliances, such as TVs and radios. In Canada, appliances that plug into a wall socket use electric power that flows back and forth at a power frequency of 60 cycles per second (60 hertz).

Every time you use electricity and electrical appliances, you are exposed to electric and magnetic fields (EMFs) at extremely low frequencies (ELF). The term "extremely low" is used to describe any frequency below 300 hertz. EMFs produced by the transmission and use of electricity belong to this category.

Electric and Magnetic Fields (EMFs)

Electric and magnetic fields are invisible forces that surround electrical equipment, power cords and wires that carry electricity, including outdoor power lines. You cannot see or feel EMFs.

Electric Fields: These are formed whenever a wire is plugged into an outlet, even when the appliance is not turned on. The higher the voltage, the stronger the electric field.

Magnetic Fields: These are formed when electric current is flowing within a device or wire. The greater the current, the stronger the magnetic field.

Electric and magnetic fields can occur separately or together. For example, when you plug the power cord for a lamp into a wall socket, it creates an electric field along the cord. When you turn the lamp on, the flow of current through the cord creates a magnetic field. Meanwhile, the electric field is still present.

The Strength of EMFs

Electric and magnetic fields are strongest when close to their source. As you move away from the source, the strength of the fields fades rapidly. This means you are exposed to stronger electric and magnetic fields when standing close to a source (e.g., right beside a transformer box or under a high voltage power line), and you are exposed to weaker fields as you move away. When you are indoors at home, the magnetic fields from high voltage power lines and transformer boxes are weaker than those from household electrical appliances.

Canadian Exposures to EMFs at ELF

On a daily basis, most Canadians are exposed to EMFs generated by household wiring, fluorescent lighting, and any electrical appliance that plugs into the wall, including hair dryers, vacuum cleaners and toasters. In the workplace, common sources include video display terminals (computer monitors), air purifiers, photocopiers, fax machines, fluorescent lights, electric heaters and electric tools in machine shops, such as drills, power saws, lathes and welding machines.

Exposures in Canadian Homes, Schools and Offices Present No Known Health Risks

Research has shown that EMFs from electrical devices and power lines can cause weak electric currents to flow through the human body. However, these currents are much smaller than those produced naturally by your brain, nerves and heart, and arenot associated with any known health risks.

There have been many studies about the effects of exposure to electric and magnetic fields at extremely low frequencies. Scientists at Health Canada are aware that some of these studies have suggested a possible link between exposure to ELF fields and certain types of childhood cancer. The International Agency for Research on Cancer (IARC) has evaluated the scientific data and has classified ELF magnetic fields as being "possibly carcinogenic" to humans. IARC based this classification on the following:

- human health population studies showing weak evidence of an association with childhood leukemia; and
- a large database of laboratory study results showing inadequate evidence of an association with cancer in animals.

To put this into context, it is important to understand that the "possibly carcinogenic" classification is also applied to coffee, gasoline engine exhaust and pickled vegetables, and is often used for agents that require further study. In summary, when all of the studies are evaluated together, the evidence suggesting that EMFs may contribute to an increased risk of cancer is very weak.

Concerns about Electromagnetic Interference

In certain circumstances, EMFs can cause interference with electronic devices. For example, office workers may notice image movement (jitter) on their computer screens if the computer is in an area where magnetic fields are slightly elevated above background levels. Some sources that generate these slightly elevated levels are the cables that bring electrical power into an office area, and common electrical equipment, such as power transformers.

Magnetic fields that are capable of causing jitter on computer screens do not present any known risks to human health. To solve the jitter problem, simply move the computer to another part of the room where the magnetic fields are weaker.

Minimizing Your Risk

You do not need to take action regarding daily exposures to electric and magnetic fields at extremely low frequencies. There is no conclusive evidence of any harm caused by exposures at levels found in Canadian homes and schools, including those located just outside the boundaries of power line corridors.

Health Canada's Role

Health Canada, along with the World Health Organization, monitors scientific research on EMFs and human health as part of its mission to help Canadians maintain and improve their health. At present, there are no Canadian government guidelines for exposure to EMFs at ELF. Health Canada does not consider guidelines for the Canadian public necessary because the scientific evidence is not strong enough to conclude that exposures cause health problems for the public.

Some national and international organizations have published health-based exposure guidelines for EMFs at ELF. However, these guidelines are not based on a consideration of risks related to cancer. Rather, the point of the guidelines is to make sure that exposures to EMFs do not cause electric currents or fields in the body that are stronger than the ones produced naturally by the brain, nerves and heart. EMF exposures in Canadian homes, schools and offices are far below these guidelines.

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Electric and Magnetic Fields At Extremely Low Frequencies

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Also, see the following Fact Sheets on the World Health Organization (WHO) Web sections:
Electromagnetic Fields and Public Health: Exposure to Extremely Low Frequency Fields, at:
www.who.int/mediacentre/factsheets/fs322/en/index.html

Electromagnetic Fields and Public Health: Extremely Low Frequency(ELF), at:
www.who.int/docstore/peh-emf/publications/facts_press/efact/efs205.html

Electromagnetic Fields and Public Health: Extremely Low Frequency Fields and Cancer, at: www.who.int/docstore/peh-emf/publications/facts_press/efact/efs263.html

For more information visit the following Web sites:
The International Agency for Research on Cancer (IARC), Static and extremely low frequency (ELF) electric and magnetic fields. Report No. 80, at:
www.iop.org/EJ/abstract/0952-4746/21/3/604

IARC Carcinogen Classifications, at:
http://monographs.iarc.fr/ENG/Classification/index.php

The U.S. National Institute of Environmental Health Sciences (NIEHS), Questions and Answers about EMF at :
www.niehs.nih.gov/health/topics/agents/emf/

It's Your Health, Safety of Exposure to Electric and Magnetic Fields from Computer Monitors and Other Video Display Terminals at :
www.hc-sc.gc.ca/hl-vs/iyh-vsv/prod/monit-eng.php

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Appendix 3

Relevant Epidemiology Studies Published after the WHO Report by Health Outcome

Relevant epidemiology studies published after the WHO report by health outcome

Authors	Study Title	Journal
Childhood Leukemia		
Abdul Rahman HI, Shah SA, Alias H, et al.	A case-control study on the association between environmental factors and the occurrence of acute leukemia among children in Klang Valley, Malaysia.	Asian Pac J Cancer Prev 9:649-652, 2008
Fezei AA and Arabi MA.	Acute childhood leukemias and exposure to magnetic fields generated by high voltage overhead power lines – a risk factor in Iran	Asian Pac J Cancer Prev 8:69-72, 2007
Foliart DE, Pollack BH, Mezei G.	Magnetic field exposure and long-term survival among children with leukaemia	Br J Cancer 94:161-164, 2006
Foliart DE, Mezei G, Iriye R, et al.	Magnetic field exposure and prognostic factors in childhood leukemia	Bioelectromagnetics 28:69-71, 2007
Greenland S and Kheifets L.	Leukemia attributable to residential magnetic fields: Results from analyses allowing for study biases	Risk Anal 26:471-482, 2006
Hug K, Grize L, Seidler A, et al.	Parental occupational exposure to extremely low frequency magnetic fields and childhood cancer: a German case-control study	Am J Epidemiol 171:27-35, 2010
Kheifets L, Ahlbom A, Crespi CM, et al.	Pooled analysis of recent studies on magnetic fields and childhood leukaemia	Br J Cancer 103:1128-1135, 2010
Kroll ME, Swanson J, Vincent TJ, Draper GJ.	Childhood cancer and magnetic fields from high-voltage power lines in England and Wales: a case-control study	Br J Cancer 103:1122-1127, 2010
Malagoli C, Fabbi S, Teggi S, et al.	Risk of hematological malignancies associated with magnetic fields exposure from power lines: a case control study in two municipalities in northern Italy.	Environ Health 9:16, 2010
Maslanyj M, Simpson J, Roman E, et al.	Power frequency magnetic fields and risk of childhood leukaemia: Misclassification of exposure from the use of the 'distance from power line' exposure surrogate	Bioelectromagnetics 30:183-188, 2009
Mejia-Arangure JM, Fajardo-Guitierrez A, Perez-Saldivar ML, et al.	Magnetic fields and acute leukemia in children with Down syndrome	Epidemiology 18:158-161, 2007
Mezei G and Kheifets L.	Selection bias and its implications for case-control studies: A case study of magnetic field exposure and childhood leukaemia	Int J Epidemiol 35:397-406, 2006
Mezei G, Spinelli JJ, Wong P, et al.	Assessment of selection bias in the Canadian case-control study of residential magnetic field exposure and childhood leukemia	Epidemiology 29:424-430, 2008a
Pearce MS, Tupitsyn AN, Legros A, et al.	Paternal occupational exposure to electro-magnetic fields as a risk factor for cancer in children and young adults: A case-control study from the North of England	Pediatr Blood Cancer 49:280-286, 2007
Schüz J, Svendsen AL, Linet MS, et al.	Nighttime exposure to electromagnetic fields and childhood leukemia: An extended pooled analysis	Am J Epidemiol 166:263-269, 2007
Svendson AL, Weihkopf T, Kaatsch P, et al.	Exposure to magnetic fields and survival after diagnosis of childhood leukemia: An extended pooled analysis	Cancer Epidemiol Biomarkers Prev 16:1167-171, 2007
Sohrabi MR, Tarjoman T, Abadi A, et al.	Living near overhead high voltage transmission power lines as a risk factor for childhood acute lymphoblastic leukemia: a case-control study	Asian Pac J Cancer Prev 22:423-427, 2010

Authors	Study Title	Journal
Yang Y, Jin X, Yan C, et al.	Case-only of interactions between DNA repair genes (hMLH1, APEX1, MGMT, XRCC1, and XPD) and low frequency electromagnetic fields in childhood acute leukemia	Leukemia & Lymphoma 49:2344-2350, 2008
Childhood Brain Cancer		
Hug K, Grize L, Seidler A, et al.	Parental occupational exposure to extremely low frequency magnetic fields and childhood cancer: a German case-control study	Am J Epidemiol 171:27-35, 2010
Kheifets L, Ahlbom A, Crespi CM, et al.	A pooled analysis of extremely low-frequency magnetic fields and childhood brain tumors	Am J Epidemiol 172:752-761, 2010
Li P, McLaughlin J, Infante-Rivard C.	Maternal occupational exposure to extremely low frequency magnetic fields and the risk of brain cancer in the offspring	Cancer Causes Control 20:945-955, 2009
Mezei G, Spinelli JJ, Wong P, et al.	Residential magnetic field exposure and childhood brain cancer: a meta-analysis	Am J Epidemiol 167:1504-1510, 2008b
Saito T, Nitta H, Kubo O, et al.	Power-frequency magnetic fields and childhood brain tumors: a case-control study in Japan	J Epidemiol 20:54-61, 2010
Adult Brain Cancer and Lymphohematopoietic Cancers		
Coble JB, Dosemeci M, Stewart PA, et al.	Occupational exposure to magnetic fields and the risk of brain tumors	Neuro Oncol 11:242-249, 2009
Forssén UM, Lonn S, Ahlbom A.	Occupational magnetic field exposure and the risk of acoustic neuroma	Am J Ind Med 49:112-118, 2006
Gobba F, Bargellini A, Scaringi M, et al.	Extremely low frequency-magnetic fields (ELF-EMF) occupational exposure and natural killer activity in peripheral blood lymphocytes	Sci Total Environ 15:407:1218-1223, 2009
Johansen C, Raaschou-Nielsen O, Olsen JH, et al.	Risk for leukaemia and brain and breast cancer among Danish utility workers: A second follow-up.	Occup Environ Med 64:782-784, 2007
Karipidis K, Benke G, Sim M, et al.	Occupational exposure to power frequency magnetic fields and risk of non-Hodgkin lymphoma.	Occup Environ Med 64:25-29, 2007a
Karipidis K, Benke G, Sim MR, et al.	Occupational exposure to low frequency magnetic fields and the risk of low grade and high grade glioma	Cancer Causes Control 18:305-313, 2007b
Kaufman DW, Anderson TE, Issagragrisil S.	Risk factors for leukemia in Thailand	Ann Hematol 88:1079-1088, 2009
Kheifets L, Monroe J, Vergara X, et al.	Occupational electromagnetic fields and leukemia and brain cancer: An update to two meta-analyses	JOEM 50:677-688, 2008
Lowenthal RM, Tuck DM, Bray IC.	Residential exposure to electric power transmission lines and risk of lymphoproliferative and myeloproliferative disorders: A case-control study	Intern Med J 37:614-619, 2007
Richardson DB, Terschuren C, Hoffmann W.	Occupational risk factors for non-Hodgkin's lymphoma: A population-based case-control study in northern Germany	Am J Ind Med 51:258-268, 2008
Röösli M, Lörtscher M, Egger M, et al.	Leukaemia, brain tumors and exposure to extremely low frequency magnetic fields: Cohort study of Swiss railway employees	Occup Environ Med 64:553-559, 2007a

Authors	Study Title	Journal
Wong O, Harris F, Wang Y, et al.	A hospital-based case-control study of non-Hodgkin lymphoid neoplasms in Shanghai: Analysis of personal characteristics, lifestyle, and environmental risk factors by subtypes of the WHO classification	J Occup Environ Med 52:39-53, 2010
Breast Cancer		
Chen C, Ma X, Zhong M, et al.	Extremely low-frequency electromagnetic fields exposure and female breast cancer risk: a meta-analysis based on 24,338 cases and 60,628 controls.	Breast Cancer Res Treat 123:569-576, 2010
Davis S and Mirick DK.	Residential magnetic fields, medication use, and the risk of breast cancer.	Epidemiology 18:266-299, 2007
Davis S, Mirick DK, Chen C, et al.	Effects of 60-Hz magnetic field exposure on nocturnal 6-sulfatoxymelatonin, estrogens, luteinizing hormone, and follicle-stimulating hormone in healthy reproductive-age women: results of a crossover trial.	Ann Epidemiol 16:62-631, 2006
Johansen C, Raaschou-Nielsen O, Olsen JH, et al.	Risk for leukaemia and brain and breast cancer among Danish utility workers: A second follow-up.	Occup Environ Med 64:782-784, 2007
McElroy JA, Egan KM, Titus-Ernstoff L.	Occupational exposure to electromagnetic field and breast cancer risk in a large, population-based, case-control study in the United States.	J Occup Environ Med 49:266-274, 2007
Ray RM, Gao DL, Li W, et al.	Occupational exposures and breast cancer among women textile workers in Shanghai	Epidemiology 18:383-392, 2007
Neurodegenerative diseases		
Andel R, Crow M, Feytching M, Pedersen N, et al.	Work-related exposure to extremely low-frequency magnetic fields and dementia: results from the population-based study of dementia in Swedish twins	J Gerontol A Biol Sci Med Sci 65:1220-1227, 2010
Davanipour Z, Tseng CC, Lee PJ, et al.	A case-control study of occupational magnetic field exposure and Alzheimer's disease: results from the California Alzheimer's Disease Diagnosis and Treatment Centers.	BMC Nrueol 7:13, 2007
García AM, Sisternas A, Hoyos SP.	Occupational exposure to extremely low frequency electric and magnetic fields and Alzheimer disease: a meta-analysis.	Int J Epidemiol 37:329-340, 2008
Huss A, Spoerri A, Egger M, et al.	Residence near power lines and mortality from neurodegenerative diseases: longitudinal study of the Swiss population.	Am J Epidemiol 169:167-175, 2009
Seidler A, Geller P, Nienhaus A, et al.	Occupational exposure to low frequency magnetic fields and dementia: a case-control study.	Occup Environ Med 64:108-114, 2007
Sorahan T and Kheifets L.	Mortality from Alzheimer's, motor neurone and Parkinson's disease in relation to magnetic field exposure: findings from the study of UK electricity generation and transmission workers, 1973-2004.	Occup Environ Med 64:820-826, 2007
Reproductive and Developmental Effects		
Auger N, Joseph D, Goneau M, et al.	The relationship between residential proximity to extremely low frequency power transmission lines and adverse birth outcomes	J Epidemiol Community Health 65:83-85, 2010
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