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HVDC Power Transmission Environmental Issues Review

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EXECUTIVE SUMMARY
TASK 2 - ENVIRONMENTAL ISSUES REVIEW

Introduction

Environmental issues are addressed in the permitting process of every transmission line project, whether it be a new line or an upgrade of an existing line. In recent years, the most controversial issue associated with alternating current lines is the potential effects of electromagnetic fields on human health. However, environmental effects on animals, plant life and other electrical and communication systems also must be assessed in every case. Although different from ac lines, high voltage direct current (HVDC) lines also produce environmental effects that warrant review and assessment in every project. This report strives to define the various environmental effects associated with HVDC lines, discusses the current knowledge of their potential effects on biological and non-biological systems, and compares these effects associated with ac lines where appropriate.

The Environment Near an Electric Power Line

The electrical environment of a high voltage transmission line can be characterized by three electrical parameters: 1) the electric field, 2) the air ion and charged aerosol concentration, and 3) the magnetic field. The electric field arises from both the electric charge on the conductors and for an HVDC transmission line, charges on air ions and aerosols surrounding the conductor. In addition, corona may also produce low levels of ozone, audible noise, electric field and radio interference. A magnetic field is produced by current flowing through the conductors. High voltage ac and HVDC lines differ in these characteristics. The electric and magnetic fields of an HVDC line are static, i.e. constant under normal operating conditions. The electric and magnetic fields of an ac line vary at 60 Hz. Ions produced by corona on ac line are neutralized by the time-varying fields so they are not an issue. Air ions produced by HVDC lines form clouds and drift away from the line and may come in contact with humans, animals and plants outside of the transmission right-of-way. Indeed, ions have been the focus of extensive research as noted in this report.

Summary of Key Findings

Ions. Neither the animal nor human studies provide any reliable evidence for the proposition that air ions produce any harmful effects. In fact, there is considerable uncertainty as to whether there are any biological responses to air ions. At the levels produced by HVDC transmission lines, the possibility of risk to human health appears remote, if not vanishingly small. There are no published guidelines for maximum exposures to air ions. However, measurements have shown that exposure naturally-occurring ions near a waterfall or seashore would be about the same as adjacent to an HVDC line right-of-way.

Electric fields: There is no mechanism to explain how exposure to external static electric fields could produce adverse biological responses. The database of studies is small. The experiments overall do not indicate a clear pattern of effect, and provide no basis to conclude that exposure to electric fields, such as those associated with the electric field of a HVDC transmission line, pose health concerns. Guidelines for the general public issued by The National Radiological Protection Board (NRPD) are limited to the avoidance of the effects of surface charge. For most people, the annoying perception of surface electric charge, acting directly on the body, will not occur during exposure to static electric field strengths of less than about 25 kV/m.

Magnetic fields: Studies of animals and humans do not indicate that exposures to dc magnetic fields up to 20 G would result in adverse health outcomes. Avian or animal migration or behavior can be influenced by dc magnetic fields. The magnetic field at the edge of a typical right-of-way of an HVDC transmission line in North America will be approximately 10 % higher or lower than the magnetic field of the earth - the earth's magnetic field is less than 1 G. For this reason alone, it seems unlikely that this small contribution by HVDC lines to the background geomagnetic field would be a basis for concern. The NRPB has considered it appropriate to restrict the time weighted exposure over any 24 hour period to 2,000 G, which represents one-tenth the established threshold for acute responses based on studies of occupational exposures to static magnetic fields.

In contrast to the studies on dc magnetic fields, the studies on ac magnetic fields have been more controversial. In fact, public concern over the siting of ac power lines focuses on ac magnetic fields. To date, the scientific research has not allowed one to conclude that exposure to ac magnetic fields is associated with any adverse health effects. However, the research on ac magnetic fields is much more complex and raises more questions than the research with dc magnetic fields. Recently, resonance theories have been proposed to explain how of ac magnetic fields might produce biological responses only in conjunction with dc magnetic fields of appropriate orientation and intensity. However, the theoretical, experimental and practical support for these theories is weak.

Effects on other Electrical and Communication Systems: There are well known effects on non-biological systems from power lines, be they ac or dc. Those effects are measurable and schemes are available to mitigate the adverse effects or reduce them to tolerable levels. They are too numerous to list here but the report provides a thorough discussion of both effects and their mitigation.

Public Perception is Key

While this research has confirmed that there is no established proof that environmental effects on biological systems are harmful, the public is still concerned. Every transmission project should begin, early on, with a public education mission. In the case of HVDC especially, there is the novelty of an unfamiliar technology to deal with since not too many citizens even know that HVDC transmission exists, let alone that it is a proven technology. Substantial precedent exists now with HVDC lines operating in the United States for 25 years. Most of those lines met with resistance on various grounds, some of which revolved around potential health effects on humans and animals. Histories exist in each case, and are summarized in this report. Future HVDC projects should build an early case based on these successes and take it public early in the planning process.

Much of the focus on perceived health effects of transmission lines appears in permitting hearings as a smoke screen to cover the real objections that are entirely separate from health issues. The visual impact of the line perhaps, or the impact on local wild life habitat may be the main issue in the end. Those and the NIMBY (not in my back yard) motives for objection, not covered in this research, will prevail apart from the biological effects issues. The well prepared transmission developer will be prepared with as much information as possible on all possible points of objection. As far as the subject of this research, the following table summarizes the state of the industry's knowledge.

Table S.1

HVAC VERSUS HVDC: POTENTIAL HEALTH IMPACTS OF ELECTRICAL ENVIRONMENT		
	AC	**DC**
Air Ions	**Not relevant**	**No observed effects**
Electric Fields	**No observed effects**	**No observed effects**
Magnetic Fields	**- No cause & effect is established** **- Research is continuing**	**No observed effects**

Conclusion

No utility has attempted to site any HVDC transmission lines since the late 1980's. Since that time, interest in potential health effects of air ions (the primary area of question for HVDC) has completely diminished, and no recent studies have raised health concerns. The resonance theories concerning interacting ac and dc magnetic fields and possible health effects could arise if new HVDC lines and converted ac circuits collocate on existing ac towers or rights-of-way.

In a persisting climate of general public concern and opposition to ac transmission lines and facilities, the siting of HVDC transmission lines may not be easier than a comparable ac transmission line, despite supposed lesser environmental impacts. Experience has demonstrated that the acceptability of transmission lines is strongly influenced by public perception of, and reaction to, many aspects of the siting and certification processes. If these processes do not develop optimally, then public concern about potential health impacts of the transmission line electrical environment may be substantially heightened.

1. INTRODUCTION

Electricity in our homes and workplaces is transmitted over considerable distances from generation sources to distribution systems. Electricity can be transmitted as alternating current (ac) or direct current (dc). AC electricity is common to all homes and to the electric lines that deliver power to our neighborhoods, factories and commercial establishments. For ac, the voltage and current oscillate from positive to negative a number of times per second, that number being the frequency. For dc, the magnitude of the voltage and polarity of the current remain steady.

Most of the high voltage transmission in the world is in the form of high voltage alternating current (HVAC). Since the development of the transformer, ac power can be generated, transmitted, distributed and used at different and convenient voltages. However, with the proper equipment, ac can be converted to dc electricity. High voltage direct current (HVDC) transmission of power can be both more efficient and less costly for transporting large quantities of power over long distances.

Electric utilities need to construct thousands of miles of new high voltage transmission lines in the next decade, but face mounting opposition to the siting of HVAC transmission lines. Although health research to date does not allow one to conclude that exposure to ac magnetic fields from power lines causes cancer or other adverse effects, the opponents of transmission projects have raised concerns about possible health effects (A review of the Potential Health Implications of AC Magnetic Field Exposure is provided as an **Appendix**). This public opposition has led to the delay or cancellation of projects.

The siting of an HVDC transmission line also raises public concern about impacts on the environment and on health. Therefore, this report assesses the potential health and environmental impacts of HVDC transmission. A brief description of the electrical environment associated with HVDC transmission is presented in **(Section 2.)**. A more detailed description of the electrical environment is presented in **Section 10**. Laboratory research on biological responses associated with the major components of the HVDC electrical environment are described in the following Sections : air ions **(Section 3)**, static electric fields **(Section 4)** and static magnetic fields **(Section 5)**. Wildlife and plant studies are discussed in **Section 6**. A comparison of health impacts of HVDC transmission lines, with those of HVAC transmission lines are provided in **Section 7**. Regulations and guidelines relevant to the HVDC electrical environment will also be described in **Section 8**. Finally, public perception and siting issues of HVDC transmission are described in **Section 9**.

2. ELECTRICAL ENVIRONMENT[1]

A HVDC transmission line has two conductors with voltages of opposite polarity, one positive and one negative. These voltages remain nearly constant, while the electrical current through the line varies depending on the demand for electricity. The environment surrounding a HVDC transmission line can be primarily characterized by three electrical parameters: the electric field, the air ion concentration, and the magnetic field. The electric field arises from both the electric charge on the conductors and air ions surrounding the conductor. Air ions are charged air molecules produced by "corona" that results from the electric field on the surface of conductors. In addition, corona may also produce low levels of ozone, audible noise, electric field and radio interference. A static magnetic field is produced by current flowing through the conductors.

2.1 CORONA AND THE PRODUCTION OF AIR IONS

Corona is a partial electrical breakdown of the air surrounding HVDC conductors. It occurs 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 two to three centimeters of the conductor. This results in the production of air ions, which are primarily derived from nitrogen and oxygen gas molecules. Positive air ions result from air molecules that have lost electrons; negative air ions are air molecules that have picked up the excess electrons.

Corona normally does not occur to a great extent when transmission line conductors are clean and smooth. However, suspended particles, dusts, liquid droplets, and sometimes insects that deposit on a conductor "enhance" the electric field at its surface, thereby forming sources of corona, and thus, sources of air ions. Corona production from HVDC conductors is therefore strongly affected by weather conditions (humidity, temperature, and precipitation) and the season of the year. In fair weather with little debris on the conductors, corona is minimal. However, operating HVDC transmission lines are generally in corona to some degree because of deposits on their surfaces and therefore almost continuously produce air ions.

Corona on a conductor of either positive or negative polarity results in the generation of positive and negative ions of the same polarity as the conductor. However, the ions having the opposite polarity to that of the conductor are drawn to it and neutralized on contact. Thus, a positive conductor in corona acts as a source of positive ions and vice versa. Since the voltage on the HVDC conductors does not change polarity as it does on an HVAC line, the air ions continuously move away from the conductors.[2] Most of the ions generated from HVDC

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[1] A more detailed description of the electrical environment is provided in Section 10.

[2] When an ac 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. Therefore, there is little movement of air ions away from ac conductors that are in corona

conductors migrate to the opposite pole where they are neutralized by recombination with air ions of opposite polarity or by contacting the conductor of opposite polarity. However, a significant fraction of the ions migrate to ground or away from the transmission line (Sarma and Janischewskyj, 1969).

Transport of Air Ions from DC Conductors

Movements of air ions are influenced by the dc electric field surrounding the conductors and by wind. The dc electric field primarily drives the electrically charged air ions toward the ground, with a few being driven upward above the line (Figure 2.1).

Other Sources of Air Ions

Air ions are present everywhere in our environment, not just near dc transmission lines. For example, clean rural air typically contains around 500 to 2,000 small positive ions/cm^3 and a slightly smaller number of negative ions (Kotaka, 1978). Many very common man-made and natural phenomena can alter this value, however. Typical air ion concentrations measured at several locations are given in Table 2.1 and Figure 2.2.

Table 2.1

Typical Air Ion Concentrations at Several Locations

Conditions	Ions/cm^3
Fair weather, open spaces	70-1000
In large towns	up to 80,000
Basement family room	400-800
Same, but candle-lit (9 candles)	up to 27,600
12 inches above burning match	200,000-300,000
200 ft from small waterfall	1,500-2,000
20 ft from highway (30 veh/min)	6,900-15,000
5 ft downwind of vehicle exhaust	34,500-69,000
4 ft from negative ion generator	26,000 (-)

(from Johnson, 1982)

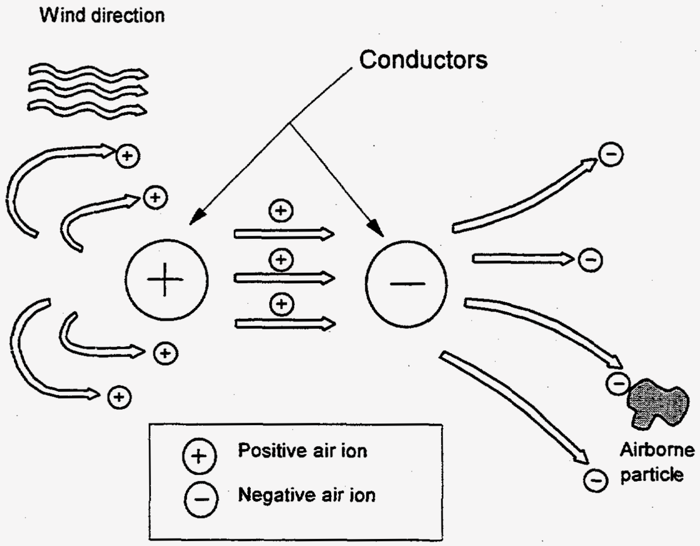

Figure 2.1: Ions drift with the wind, some fall to the ground, others move to the conductor with opposite polarity and are absorbed.

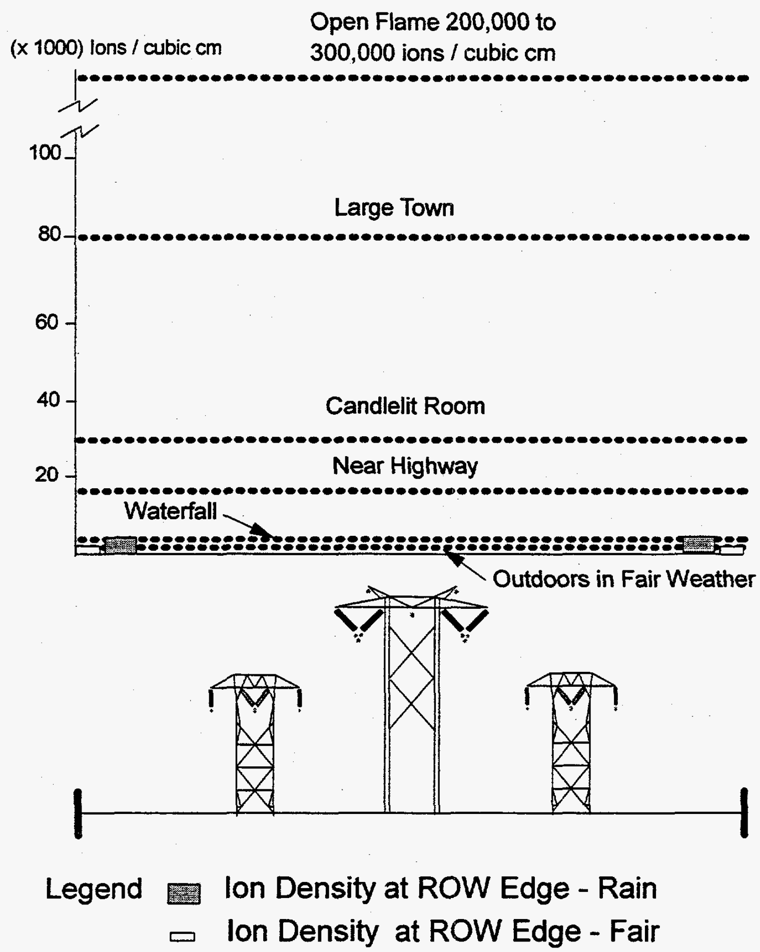

Figure 2.2 Typical ion densities on section of New England Electric's +/- 450 kV dc line between Monroe, NH and Londonderry, NH

2.2 DC ELECTRIC FIELD

An electric field is the field surrounding an electric charge, and exerts a force on other charged or uncharged objects. A dc electric field does not change direction. Static electric fields are encountered in our everyday environment -- such as when walking across a carpet or when a comb attracts one's hair on a dry day.

The electric field from a dc transmission line results from two sources: the charge on the surface of the conductors and space charge, which includes air ions and charged aerosols. The electric field associated with space charge always extends beyond the right-of-way, and the distribution of the electric field from the space charge depends on the direction and velocity of the wind.

Ion Current

Another aspect of the HVDC environment describes the combined interaction between space charge and the electric field from the line. As already stated, electric fields exert a force on charged particles. Therefore, the electric field from a transmission line exerts a force on air ions and charged aerosols.

2.3 DC MAGNETIC FIELDS

All magnetic fields have in common the movement of electric charges, but all magnetic fields are not the same. A static magnetic field is produced by magnets or dc current flow in conductors; static magnetic fields vary little in magnitude and direction over time. In contrast, a time varying magnetic field is produced by ac sources; and these fields vary in both magnitude and direction with time. This distinction between dc and ac fields has implications for the ways fields from these sources interact with objects, including biological organisms.

There are natural and artificial sources of static magnetic fields. The natural magnetic field of the Earth originates from the metallic core of the Earth and the electrical current existing in the upper layer of the Earth's crust. The strength of this field varies, being highest at the magnetic poles (~700 mG), and lowest at the equator (~200 mG). In addition to this, natural geomagnetic field, static magnetic fields are also produced artificially, by unvarying electric currents and permanent magnets. Sources of artificial static fields are produced in medical applications, energy technologies, industries and transportation vehicles. dc transmission lines are another source of magnetic fields. Magnetic fields at the edge of the right- of- way of a dc transmission line are about a tenth of the Earth's magnetic field (Figure 2.3).

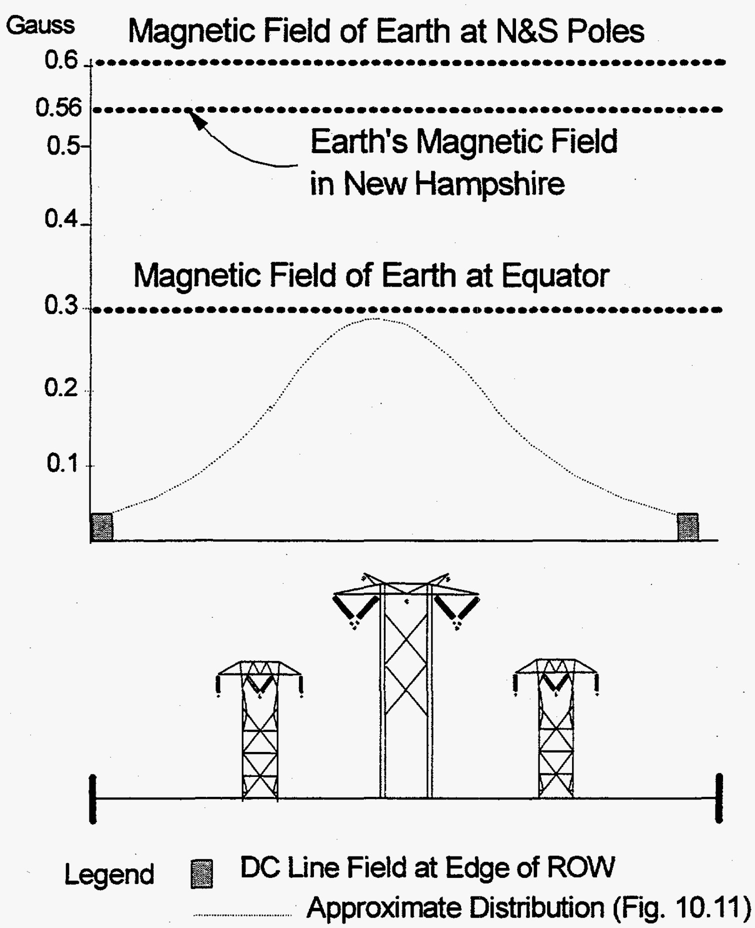

Figure 2.3 Typical magnetic field on section of New England Electric's +/- 450 kV dc line between Monroe, NH and Londonderry, NH

2.4 HARMONICS

While the predicted output of conversion of ac to dc power is a pure dc current and voltage, in practice, the conversion process leads to voltages at 60 Hz, and at odd multiples of 60 Hz - (termed harmonics) to appear in the converter output. Harmonics also appear in the output of dc to ac power convertors. For HVDC transmission lines, unwanted ac voltages are filtered out at the convertor station and so the residual harmonic voltages and currents are too weak to be a significant source of exposure to fields. An exception is within the conversion station where occupational exposures to the converted, but unfiltered, power might potentially interfere with implanted cardiac pacemakers (Bailey et al, 1982).

2.5 AIR QUALITY

In addition to the production of air ions, corona on HVDC transmission lines also leads to the production of small quantities of ozone (O_3) and nitrogen oxides (NO_x). Corona on HVAC transmission lines is a similar source of these pollutants. These pollutants are normally present in the atmosphere at levels in rural areas of about 20-25 ppb (O_3) and 2-5 ppb (NO_x). Substantially higher levels of these pollutants are found in urban areas. The primary National Ambient Air Quality Standards for these pollutants are NO_2 - 53 ppb (annual basis) and O_3 120 ppb (1 hour/day/year) [EPA, 1994]. While levels of these pollutants exceeding these standards could be expected to have impacts both on human and animal health as well as the environment (plants, wildlife), there is no theoretical basis nor empirical data to suggest that a HVDC transmission line would significantly impact ambient air quality. An early study of a +/- 500 HVDC test line only sporadically detected ozone downwind of the conductors in wet weather (Droppo, 1979). The most comprehensive study to date performed two and one-half years of pollutant and weather monitoring before and after the construction of a +/- 400 kV transmission line in Minnesota (Krupa and Pratt, 1982). 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. Only when downwind values were compared to upwind measurements could any increase be detected at all. The study also surveyed growth, condition, and diseases in crops grown in 25 plots located 30.5 m from the transmission centerline. No effects attributable to the presence of the line including ozone, NO_x, air ions, or fields were detected based upon reference data of the local Animal and Plant Health Information System.

In addition to questions about corona-generated pollutants, possible impacts of air ions on the chemical composition of the air have been investigated. Gaseous components of the air, including trace chemical contaminants, can react with air ions . The question is whether air ions generated by HVDC transmission lines are substantially different from ambient air ions generated by other sources. While earlier research provided good suggestions as to the ion species formed by corona activity in specialized laboratory conditions, it was only recently that measurement equipment has been available to determine the characteristic chemical species of air ions that are formed under HVDC transmission lines. Measurements made with a quadrapole mass spectrometer at the Pacific Northwest-Southwest Intertie transmission line indicate that the primary difference between air ions formed by corona activity and naturally occurring ions is their lifetime. Air ions generated by an HVDC transmission line persist for only 2-3 seconds while most naturally-occurring air ions have lifetimes as much as 100 times longer (Eisele, 1989; see Fig 2.4). Measurements also have been made of the chemical species of air ions formed by corona sources in exposure systems designed for biological studies (W. Bailey, Institute for Basic Research, New York, NY). These measurements suggest that the ions formed under these conditions are similar to those formed under the Pacific Intertie, although the spectrum of ions formed, both by the transmission line and ion sources in the laboratory, is influenced by the chemical composition of air where the ions are generated (Eisele, 1989).

2.6 OPPORTUNITIES FOR EXPOSURE

In evaluating HVDC transmission lines as potential sources of exposure to air ions and fields, one must be aware that exposure calculated at a particular distance from the line may not represent an effective exposure for a variety of reasons. For example, persons indoors are largely shielded by conductive building materials from fluctuations in the intensity of dc electric fields and air ions out-of-doors but not magnetic fields. The conductive tissues at the surface of the body similarly serve to shield tissues below the surface from external electric fields and ions. Air ions that are inhaled, however, do have access to the mouth and upper respiratory tract (Pavlik, 1967; Ingham, 1981). Neither building materials nor the body block magnetic fields.

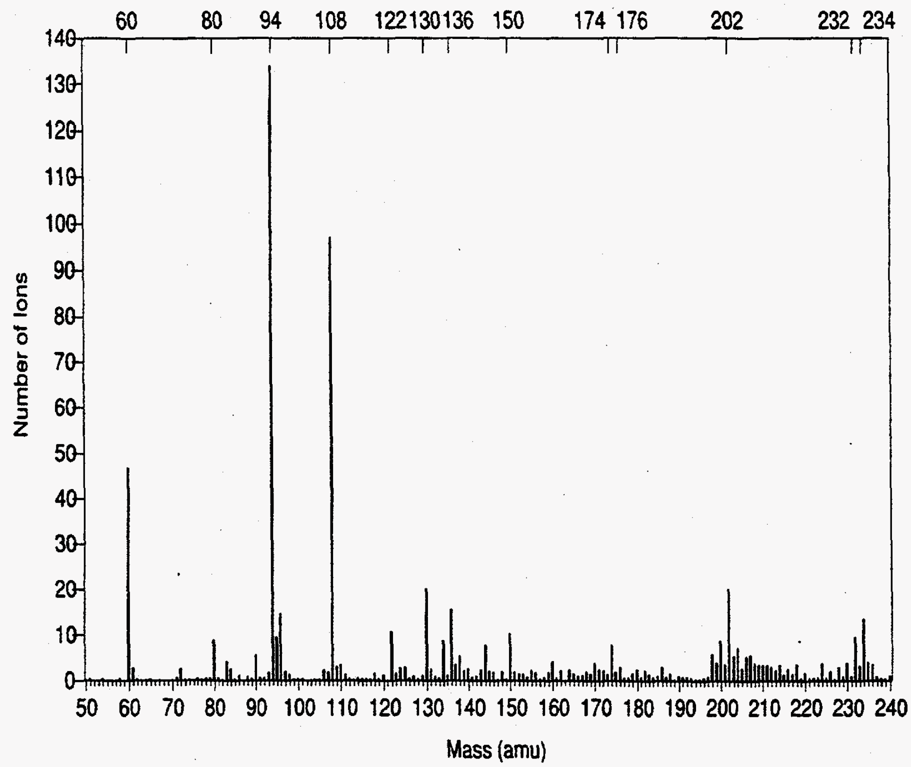

Figure 2.4: Averages of several measurements of the positive air ion mass spectrum observed under the positive conductor of the +/- 500 kV Pacific Intertie. (from Eisel, 1989)

3. AIR IONS

Almost since the discovery of ionized 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 in which air ions have been reported to affect animals, humans, and lower organisms (microorganisms, plants). Laboratory studies of humans and animals have evaluated a wide range of exposures ranging from ambient levels (about 1000 ions/cm^3), to levels in the range of those found directly under a HVDC transmission line (i.e., about 100,000 ions/cm^3), and to very much higher levels (1,000,000,000 ions/cm^3).

In studies of biological effects of air ions, there are few studies of substantial depth and quality. Virtually no findings in air ion research have been verified by other independent investigators. The complete absence of any confirmed findings of scientific or health significance apparently has led investigators to study other research topics. Less than five peer reviewed papers on air ions has been published in the literature since 1992, and one of these papers (Creim et al, 1995) describes research completed in 1986.

One problem with air ion studies is that air ions have been generated in many different ways with little regard to accurately measuring ion levels or providing adequate experimental controls. Other problems with the studies are that environmental factors, particularly those associated with the generation of air ions and dc electric fields - ozone, light, noise - have not been adequately controlled. Thus, effects attributed to the experimental variable may merely reflect these confounding exposures.

Table 3.1

Miscellaneous Factors Which Can Influence the Outcome of Experiments Involving the Exposure of Organisms to Air Ions
Experimenter bias
Instructions and explanations given to human subjects
Static charge - microshocks
Grounding of subject
Ambient air quality - pollutants
Atmospheric variables, e.g., temperature, humidity
Factors often associated with ion generation by corona discharge Electric field Ozone, oxides of nitrogen Noise Ultraviolet light
Physiological state, e.g., age, autonomic responsiveness

The problem of ozone exposure in the air ion studies warrants special mention. Ozone and oxides of nitrogen are bi-products of corona discharge that are used to generate air ions in many laboratory exposure systems. However, unless the conditions are optimized to minimize the generation of these pollutants and to facilitate their diffusion away from the animal or tissue under study, effects of ozone are observed that might be mistakenly attributed to air ions. For example, it has been claimed that negative air ions alter a critical enzyme for cell energy, ATPase activity of mouse cells (as measured by the reduced transport of ^{86}Rubidium- a radioactive element often used as a marker for the transport of calcium into cells) and produce swelling of the cells (Jaskowski and Mysliwski, 1986, Jaskowski et al, 1986b; Witkowski and Mysliwski, 1986). However, reduced transport of ^{86}Rb and cell swelling are characteristic toxic responses to ozone (Koontz and Heath, 1979), and the effects of negative air ions on isolated red blood cells (lysis, hemoglobin destruction) cannot be distinguished from the effects of ozone (Goheen et al, 1983, 1985).

3.1 MECHANISM OF INTERACTION

Because air ions are simply air molecules that have gained or lost electrical charges, it is understandable that investigation as to their effects would focus on the respiratory system and the skin. Air ion interactions with the body are therefore similar to other components of air except that charged particles can be attracted and deposited on the skin and respiratory tract by electrostatic forces as well. Consideration of such forces suggests that most of the air ions would be retained in the nose and bronchi with none reaching the deep alveoli of the lung (Bailey et al, 1982).

In addition to air ions, the effect of charge transfer from small air ions to larger aerosols should be considered. This route of interaction of space charges with the body has been given less attention. This is because about two-thirds of ambient aerosols are already charged to some degree, so the modest shift in the proportions of aerosols that are charged due to an HVDC transmission line does not represent the same degree of perturbation of the environment as does the generation of air ions. The question has been raised, however, whether the health impact of aerosols is altered by the addition of electrical charge from an HVDC line (Bailey et al, 1982).

Laboratory studies have demonstrated that large amounts of charge on aerosol particles increases 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 (expressed in multiples of Q, the charge on a single electron) 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 smokes generally have diameters less than 1.0 μm.)

These experimentally determined thresholds for enhancement of deposition are higher than both predicted and measured values for the charge acquired by most aerosol particles from collision with air ions from an HVDC transmission line. Hoppel (1980) has calculated the median charge on particles of different sizes as a function of particle concentration and charging time for particles carried downwind of an HVDC transmission line. His results suggest that few aerosol particles less than 1.0 μm in diameter acquire a charge greater than 10 Q. Experimental measurements of the charge on particles near an HVDC test line indicate that fewer than 6 Q per particle are measured on particles sampled downwind of the transmission line (Johnson and Zaffanella, 1985). Thus, the amount of charge present on individual aerosol particles from an HVDC line will likely almost always be below experimentally determined thresholds for enhanced deposition of aerosol in the respiratory tract. These data indicate there is little reason to believe that the addition of minor amounts of charge to aerosols by an HVDC transmission line would have any health significance.

Surprisingly, however, much more research has targeted potential effects on behavior and the central nervous system in spite of there being no immediately obvious reason for such an interaction. This interest derives from an idiosyncratic historical focus on behavioral responses to air ions and the search for possible therapeutic effects (e.g., Dessauer, 1931; Herrington, 1935; Silverman and Kornblueh, 1957; McGurk, 1959; Minkh, 1961).

3.2 ANIMAL STUDIES

Behavioral and Physiological Arousal

One of the few apparently consistent effects reported in the literature is that exposure to high concentrations of negative ions for short periods (minutes) increases the behavioral reactivity of rats. Negative ions at concentrations of 10^4 to 10^6 are reported to increase the arousal of rodents as measured by: running wheel activity (Herrington, 1935); struggling activity in restraint cages (Bachman et al, 1966a); spontaneous motor activity (Olivereau, 1970c; Lenkiewicz et al, 1989); and exploratory activity (Olivereau and Lambert, 1981; Dabrowska et al, 1991). However, when animals were exposed to negative air ions in combination with defined levels of dc electric fields, no such responses were observed (Bailey and Charry, 1986; Gromyko and Krivodaeva, 1992). Positive ions have been reported to have no effect (Bailey and Charry, 1986), or an opposite effect to negative ions (Olivereau, 1970c). One study reported increased activity after repeated daily exposures for 154 days. It is not possible to differentiate if the animals were responding to air ions or to some other factor, e.g., ozone, high frequency noise, that also produced by the exposure system.

The importance of factors other than air ions in affecting behavioral arousal is strongly supported by studies in which exposures to animals were administered in specially constructed chambers where gaseous by-products of corona discharge (O_3 and NO_2) were minimal and temperature, humidity, and noise level were controlled, so as not to be confounding factors (Charry et al, 1986). When the spontaneous motor activity of animals was measured during exposure to air ions at a concentration of 10^5 ions/cm^3 or to purified air, over 5-minute intervals for periods up to 66 hours, no effects of exposure were observed (Bailey and Charry, 1986).

Studies of physiological indices of arousal, such as heart rate, respiration, and electrical activity of the brain, do not show profound or consistent responses. Heart rate has been reported to both increase with exposure to positive or negative ions or to decrease with either (Bachman et al, 1965; McDonald et al, 1965) at air ion levels from 350,000 to 530,000 ions/cm^3.

Respiratory rate, in the same two sets of experiments, was found to increase in one in response to either species of ion (Bachman et al, 1965), but was not affected in the other (McDonald et al 1965). However, two studies have reported that exposure of rats to negative ions increased EEG activity while exposure to positive ions decreased EEG activity during exposures of about 80,000 air ions/cm^3 (Lambert et al, 1981; Olivereau et al, 1981).

Learning and Performance

In animal studies of learning and performance, often the motivation for the animals behavior is to avoid an unpleasant stimulus, e.g., a mild electric shock. Several studies have reported that positive air ions at concentrations of 100,000 to 600,000 ions/cm^3 slow such learning, while exposures to equal levels of negative ions have been reported to shorten the time for learning (Falkenberg and Kirk, 1977; Lambert and Olivereau, 1980; Olivereau and Lambert, 1981).

A second type of learning experiment requires the mastery of complex tasks, such as running or swimming through a maze. In these studies, either enhanced learning in the presence of negative ions, or no effects have been reported (Bauer, 1955; Jordan and Sokoloff, 1959; Terry et al, 1969). The outcomes of these studies appeared to be influenced by factors such as the age of the animal, and the stressfulness of pre-testing conditions. Several investigators (Olivereau, 1970a, b; Gilbert, 1973) have observed sometimes opposing responses of animals to ions of different polarity. They have attempted to correlate this with their emotional or arousal state caused by responses to painful heat stimulation or other stimuli (noise, handling). However, the data are insufficient to draw any firm conclusions.

Serotonin Metabolism

Serotonin is one of the more than 75 known chemicals that brain and nerve cells release to affect adjacent cells. This is part of the electro-chemical process by which nerves can communicate with adjacent cells and other tissues. A number of early studies suggested that exposure to positive air ions decreased the levels of serotonin in brain, while negative ions increased serotonin levels (Krueger and Kotaka, 1969; Gilbert, 1973; Diamond et al, 1980). These effects were reported to occur at exposure levels ranging from 3000 ions/cm^3 for 100 days to 500,000 ions/cm^3 for periods ranging from 12 hours to 20 days. Another study reported an elevation of brain serotonin after positive ion exposure with a decrease following negative ion exposure, using 700,000 ions/cm^3 in both cases (Beardwood et al, 1987). Three recent studies, however, using exposures of 500,000 to 1.5 million ions/cm^3 for similar periods showed no effect on serotonin or serotonin precursors and metabolites (Dowdall and de Montigny, 1985; and Bailey and Charry, 1987). In addition, Charry and Bailey (1985) failed to find any effect of air ion exposures on the concentration and utilization of norepinephrine and dopamine - two other neurotransmitters in brain (Charry and Bailey, 1985). These studies by Bailey and Charry which reported no effects on serotonin or catecholamine metabolism are the only ones conducted under carefully environmentally controlled conditions.

It has also been reported that exposure to air ions alters the serotonin content of blood in a fashion similar to that reported for brain tissue (Krueger et al, 1963, 1968). The magnitude and severity of the effect is said to depend upon the CO_2 content of the air. However, the data were quite variable and may have been affected more by fighting among the mice and the time of day samples were collected than by exposure to air ions. In any case, the range of variation in serotonin levels reported is within the range of values observed to occur normally. One source of variation in blood serotonin levels is with the intraluminal pressure of the stomach and gastrointestinal tract. For example, eating decreases the serotonin content of these tissues in the rat by 30-40%, and in humans elevates the concentration of serotonin in the blood. Conversely, fasting elevates the serotonin content of the gastrointestinal tract, but reduces the serotonin content of blood (Warner, 1967; Biggio et al, 1977).

Tracheal Function

In a pioneering series of investigations, Krueger and his colleagues reported that positive and negative air ions at a concentration of 1,000,000,000 cm^3 have opposite effects on the mucociliary and respiratory tract activity (ciliary movement, mucous secretion, vasoconstriction, respiratory rate) of five animal species which they examined (Krueger and Smith, 1957, 1958, 1959, 1960a, b; Krueger et al, 1959). Because of the apparent similarity of positive and negative air ion effects to those produced by increases and decreases in the availability of serotonin, Krueger hypothesized that air ions effects were mediated by variations in this neurohormone. However, four different investigators have attempted to replicate these findings without success (Badre et al, 1966; Guillerm et al, 1966; Kensler and Battista, 1966; Andersen, 1971, 1972). Ultimately, Krueger himself admitted that environmental factors other than air ions were probably involved (Krueger and Kotaka, 1969).

Sensitivity to Respiratory Infection

Based upon his studies of tracheal function *in vitro*, Krueger conducted an additional series of experiments on intact animals over seven years. In these experiments, Krueger examined the rate at which mice succumbed to infectious respiratory disease following exposure to air ions. The major findings were that mice exposed to air ions and then challenged with bacteria or viruses exhibited increased or decreased mortality following exposure to ions of either polarity (Krueger and Levine, 1967; Krueger et al, 1970; Krueger and Reed, 1972). However, this alleged effect was small relative to spontaneous variations in observed mortality within these experiments and the conclusions of the investigators were not supported when animals exposed to 'ion depleted' air instead of air containing air ions at ambient levels were considered as the control group.

Reproduction and Longevity

The possibility that air ions influence reproduction has been investigated. A series of three similar studies of neonatal development was undertaken by a single laboratory, in which pregnant female rats were exposed to 10,000 positive or negative ions/cm^3 for varying periods

(Hinsull et al, 1981, 1984; Hinsull and Head, 1986). Newborn rats were monitored for birth defects, body weight at birth, and survival time following birth. The first study indicated some excess mortality among newborns of exposed mothers, but the colony from which the animals had been taken was later found to be infected with a respiratory disease. This infection very likely influenced the results, because when care was taken to eliminate pre-existing infections, the last two studies showed no effects of air ion exposure on reproduction, measured over four successive generations for negative ions and two generations for positive ions.

Two other studies investigated the effects of lifelong exposures to air ions. In one study rats were exposed to 10,000 negative ions/cm^3 from age five weeks until death (Hinsull, 1988). Hinsull suggested that this chronic exposure was responsible for an increased life span of exposed animals, but the documentation and rationale for this conclusion was weak. In the other study, mice were exposed to positive or negative ions at a concentration of 200,000 ions/cm^3 and followed until death (Kellogg et al, 1985a,b; Kellogg and Yost, 1986). Body weights were measured monthly and every three months blood chemistries were analyzed. Although slightly reduced longevity and serum glucose were reported in mice exposed to air ions compared to mice exposed to dc electric fields alone, the differences in magnitude were small and confounded by a serious outbreak of intestinal infections among both exposed and control groups in the first year of the study.

Effects of HVDC Transmission Lines on Dairy Cattle

Two studies have been conducted to respond to the concerns of farmers about effects of the electrical environment of HVDC 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, 1983b). Six years of veterinary records were examined, from three years before to three years after energization of the line in 1979. For purposes of analysis, the herds were grouped according to distance of the farmstead from the transmission line, with the closest herds less than 1/4 mile of the line, and the farthest between 6 and 10 miles distant. Endpoints selected for study included milk production per cow, herd average of milk production, milk fat content, and measures of reproductive efficiency, among others. Health and productivity of the herds were found to be the same before and after energization, and were also found to be unrelated to distance of the herds from the transmission line.

A more direct test for effects of air ions, dc electric fields, or other aspects of the HVDC transmission line environment was performed by scientists at Oregon State University with the assistance and support of the Bonneville Power Administration (BPA) in the U.S. and the sponsorship of Hydro-Quebec and eight other utilities (Raleigh, 1988; Angell et al, 1990). Dairy cattle and crops were raised near an HVDC transmission line. Simulated farming and ranching conditions were set up and carefully maintained directly under the ± 500-kV Pacific Intertie in central Oregon and at an identical site 2000 feet away from the line. Exposures of the animals under the HVDC transmission line was 5 to 30 times that of the control herd for electric field, ion current, and density of ions, with average exposures being 5.6 kV/m, 4.1 nA/m^2, and 13,000 ions/cm^3, respectively. After breeding the cattle for three seasons, herds at the two sites were compared. The breeding activity, conception rate, calving, calving interval, and body mass of the two herds did not differ. No deleterious effects on cattle production or health status could be attributed to exposures from the transmission line.

3.3 HUMAN STUDIES

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 Israel for a variety of physiological conditions. However, the reported biological and behavioral responses to air ion exposures in all these studies, like the animal studies, are often inconsistent. Positive and negative ion exposures have sometimes been reported to exert opposite effects, but many studies reported no effects. The studies described below include observations of air ion effects on mood, performance, serotonin metabolism, respiratory function and other acute health effects.

Mood and Performance

Some of the earliest research on human responses to air ions focused on behavioral responses to air ions and the search for possible therapeutic effects (e.g., Dessauer, 1931; Herrington, 1935; Silverman and Kornblueh, 1957; McGurk, 1959; Minkh, 1961). 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 1960's. In an attempt to validate or refute such speculations, human volunteers have been exposed in laboratories to both negative and positive air ions at levels ranging from approximately one thousand to one million air ions/cm^3.

The effects that have been studied include physiological indices like: temperature, blood pressure, pulse rate (Yaglou et al, 1933; Herrington, 1935; Herrington and Kuh, 1938; Erban, 1959; Minkh, 1961; Albrechtsen et al, 1978), as well as a variety of cognitive and performance variables including alertness and vigilance (Chiles et al, 1960; McDonald et al, 1967; Albrechtsen et al, 1978; Brown and Kirk, 1987); and reaction time (Slote, 1961; Halcomb and Kirk, 1965; Hawkins and Barker, 1978; Tom et al, 1981). In addition, quite a few studies focused on possible effects of air ions on mood or emotional variables (Yaglou, 1961; Sigel, 1979; Charry and Hawkinshire, 1981; Hawkins, 1981; Baron et al, 1985; Deleanu and Stamatiu, 1985; Giannini et al, 1986; Hedge and Collis, 1987). During or following these exposures, which have lasted from minutes to days, the above variables were evaluated. Many of these studies reported no effects, while some did report changes. The changes found were quite small, and in many cases were less than or comparable to the range of responses observed following changes in the everyday environment (e.g., changes in temperature or humidity) [Charry, 1987].

In several studies, investigators sought to find beneficial effects on children. These studies reported either no effect (Yates et al, 1987) or small increases or decreases in performance depending upon testing conditions (Fornof and Gilbert, 1988).

Altogether, there is no consistent pattern of results from these studies that supports the idea that air ions significantly affect physiological parameters, performance, or mood. Such claims have, in the past, been disputed by the Food and Drug Administration (FDA) in the United States, which regulates manufacturers of devices making health claims (USFDA, 1980).

Serotonin Metabolism

Research on air ions in relation to serotonin metabolism consists mostly of clinical studies reported by Sulman (1970, 1975, 1978) in Israel. This investigator has hypothesized that symptoms of climatic heat stress are caused by an increase in the concentration of positive ions associated with Sharav winds. Sulman presented data purporting to show that air ions affect both clinical symptoms and the concentration of serotonin and its metabolite, 5-hydroxy indoleacetic acid (5-HIAA), in urine samples of clinic patients. However, the quality of the methods, data, and analysis are so poor that no weight can be given to these observations. Several other studies have recorded 5-HIAA levels in the urine of adults (Barron and Dreher, 1964; Sigel, 1979), or children exposed to air ions (Fornof and Gilbert, 1988) with inconsistent results. A major problem in the design of all these studies is that fluid intake was not controlled and the excretion of 5-HIAA in urine varies directly with fluid intake (Bertaccini et al, 1964).

Respiratory Function

Air ions can obviously be inhaled, and if they are physiologically active, they might be expected to influence the respiratory tract. Based upon this hypothesis and some animal studies, a number of investigators have evaluated the ability of air ion exposures to improve pulmonary function. However, quantitative experimental studies and a double-blind clinical study do not support this hypothesis (Zylberberg and Loveless, 1960; Lefcoe, 1963; Blumstein et al, 1964; Mottley and Yanda, 1966; Albrechtson et al, 1978).

There is no conclusive evidence that symptoms of respiratory distress are improved or induced by air ion exposure. Two reports indicated that exposure to 30,000 positive or negative ions/cm^3 improved lung function in people with bronchial asthma (Albrechtsen et al, 1979; Osterballe et al, 1979), but other studies claim that only negative ions improve function and that positive ions actually aggravate the condition (Bendov et al, 1983; Lipin et al, 1984). Emphysema and hay fever have been reported not to be affected by air ion exposure (Blumstein et al, 1964; Motley and Yanda, 1966). A thorough review of the studies of air ions on the respiratory system is found in Bailey et al (1982).

Effects of HVDC Transmission Lines on Humans

One of the most comprehensive evaluations of the potential effects of air ions or static fields on human health was a cross sectional study of a densely populated community through which the Pacific Intertie HVDC 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. At the time of the study (1981), it had been operating at 400-kV for almost 12 years (it now operates at 500-kV). The health endpoints surveyed among the residents included headaches, number of illness days, depression, drowsiness, and respiratory congestion. These endpoints were selected for study based upon the existing animal and human studies.

Participants in the study were divided into groups depending on how close they lived to the HVDC transmission line corridor. The "near" group lived within 0.14 miles of the corridor, and was subdivided into those people who lived right on the edge of the corridor and those who lived beyond the corridor. The "far" group lived between 0.65 and 0.85 miles from the line. The interviews were conducted by home visits, and all members in the household over the age of two were used as subjects. 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 observed, indicating no health impacts. The power of the study could have improved if actual measurements had been used to characterize persons with different exposure. Nevertheless, the study is an important contribution to our knowledge. In addition, other less controlled public health surveys have not reported that HVDC transmission lines impact self-reported health symptoms (Banks and Williams, 1983; Banks and McConnon, 1987).

3.4 SUMMARY: AIR IONS

Air ions have been studied for almost 100 years to determine whether they are able to impact biological systems. Much of this research has been focused on finding possible therapeutic benefits. The difficulty in envisioning any biological impact of air ion exposures is that air ions have no separate identity; that is, they are simply air molecules that have gained or lost electrical charges. When they recombine with one another or contact organisms, they are again ordinary neutral gas molecules. Hence, potential mechanisms by which health or environmental impacts might occur are similar to any other constituent of air.

Research on animals has focused on primarily short-term effects on behavioral and physiological indices of arousal, the metabolism of the neurohormone, serotonin, and the respiratory tract. In addition, effects of long-term exposures on reproduction and health have been assessed both in laboratory rats and in cattle living under or near operating HVDC transmission lines. Most animal studies failed to properly control and measure air ion exposures as well as other important environmental factors. Among these environmental factors, ozone production by the ion generating devices poses the most serious concern. Ozone could produce many of the reported effects attributed to air ions. Even so, the responses reported in animal studies are often small in magnitude, although the exposures are many fold greater than could be found in the vicinity of HVDC transmission lines.

Research on human subjects to a large extent parallels the research on animals. Effects on mood and performance, serotonin metabolism, and the respiratory system have been most thoroughly studied. The problems in measuring and controlling exposures in human experimental studies are similar to those observed in animal studies. Several health surveys of persons living adjacent to HVDC transmission lines have not reported a greater prevalence of acute health complaints, e.g., headaches, and respiratory congestion, than among persons living away from the lines.

Neither the animal or human studies provide evidence that air ions produce any harmful effects. In fact, there is considerable uncertainty that there are any biological responses to air ions.

4. DC ELECTRIC FIELDS

Static electric fields are produced by electrical charges. The distribution of charges in the atmosphere produces a naturally occurring static electric field between 120-150 V/m, under normal atmospheric conditions. In storm conditions, a static field of several thousands of volts per meter can be measured. Static electric fields are also found in offices and homes -- such as when walking across a carpet, where potentials can build up to 20 kV/m. Electric fields in the right-of-way of a representative HVDC transmission line range up to about 13 kV/m (Figure 4.1 and Figure 10 in Chapter 10.8).

4.1 MECHANISM OF INTERACTION

Static electric fields can be perceived, but do not penetrate the organism. A person exposed to an electric field will distort the field and enhance the strength of the field at the body surface to levels above those in the unperturbed space. Static electric fields can exert a force, for example, on body hair, which may be perceived. However, because such fields are not time varying, the electric fields induced within the body from the external field are negligible. Therefore, independent of the ability to perceive the field by the stimulation of body hair, there is no biophysical mechanism to explain how exposure to static electric fields could directly influence biological processes.

The dosimetric relationship between animal and human exposures may therefore be made on the basis of the surface electric strengths. Body sensitivity to surface fields may involve particular areas or sensory organs that are species specific (e.g., rat vibrissae), so a rigorous comparison of rat and human studies is difficult. However, to a rough approximation, exposures of a person to a 10 kV/m static electric field can be considered to be similar to a rat exposed to a 50 kV/m field.

DC fields can give rise to shocks to persons who contact large metallic objects, such as a truck, near the transmission line. Shocks occur when charges collected on the truck discharge through a person to ground.

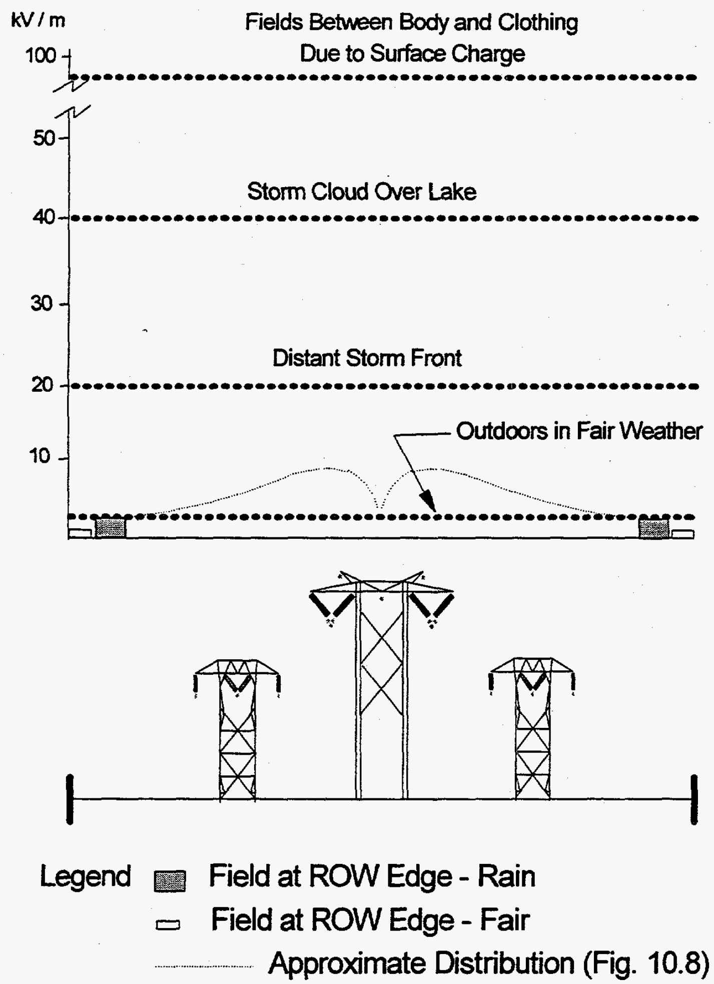

Figure 4.1 Typical electric fields on New England Electric's +/- 450 kV dc line between Monroe, NH and Londonderry, NH. Absolute magnitudes shown -- actual values are negative on one side.

4.2 ANIMAL STUDIES

Both humans and animals have been exposed to dc electric fields in experimental laboratory studies. The field strengths used in these experiments have ranged from lower than to higher than near HVDC transmission lines. Some laboratories have reported response to fields, but the large majority of data indicate that dc electric fields produce no biologically important changes. The laboratory research relevant to this question are studies involving exposure of whole animals to dc electric fields. A number of elegant studies have examined the effect of intense electric fields on isolated cells and tissues. However, since intense internal electric fields cannot be induced by external dc electric fields, these studies are not discussed in this report.

Brain and Behavior

Most of the studies of dc electric field effects on animals have focused on behavior and brain functions. It is reported that running and swimming behavior, and brain wave (EEG) activity are affected by field exposure. On the other hand, no influence of electric fields has been reported for spontaneous behavior, or brain neurochemistry.

Various aspects of behavior have been evaluated, but no consistent trend can be identified. For example, both running activity and performance of rats swimming a maze have been reported to increase with exposure to dc electric fields between 1.6 and 24 kV/m (Mayyasi and Terry, 1969; Mose and Fischer, 1970).

Bailey and Charry (1986) designed a study to examine the influence of static electric fields on behavior. Aware that many published experiments had poorly controlled exposure facilities, these investigators carefully designed the exposure system and animal facilities to prevent artefactual results. Rats exposed to fields of up to 12 kV/m for up to 66 hours did not exhibit any different spontaneous motor activity or circadian rhythms than sham-exposed controls.

Two recent studies have examined whether static electric fields are noxious to rats. Creim et al (1993) exposed rats to dc electric fields in a rectangular box and examined whether rats avoided the field. At the left or right end of the box, the rats were exposed to HVDC electric fields and air ions; the other end was sham exposed. The center of the box was a transition zone between exposure and sham exposure. In the experiments the rats could choose to be exposed to positive dc fields and ions or negative dc fields and ions. The air ion concentration was held constant. In one hour sessions, they observed no significant differences in animal location preference at field levels below 55 kV/m, but observed that the rats avoided exposure to fields at intensities greater than 55 kV/m at either polarity. Air ions at concentration of 10^5-10^6 ions/cm^3 was reported not to influence avoidance behavior. The authors hypothesize that the observed avoidance behavior is due to piloerection and subsequent cutaneous stimulation of the hair by strong fields. This mechanism is the same as that invoked to account for avoidance of ac electric fields in this same apparatus at field strengths > 75 kV/m (Hjereson et al, 1980).

In the second study, Creim et al (1995) studied whether dc electric fields and air ions could provoke illness. Taste aversion learning has been used to determine if an animal can be conditioned to associate a novel taste (saccharin-sweetened food) with another stimulus which produces internal discomfort or stress. If the animal finds this latter stimulus aversive, it will remember to avoid the novel food on subsequent trials, since it has paired this taste with the aversive stimulus. Rats have evolved this kind of learning as a survival mechanism and are therefore very sensitive to stimuli that produce 'poisoning' - type symptoms. When saccharin-flavored water is paired with dc electric fields of 75-kV/m and air ions at 200,000 ions/cm^3, Creim and his colleagues (1995) were unable to find any evidence for taste aversion learning. Therefore, electric field exposure was not perceived by these animals to cause illness or discomfort. Their experimental procedures were validated by positive controls; taste aversion learning did take when the taste was paired to cyclophosphamide that induces nausea. This experiment reinforced that avoidance of location with high dc fields and ions in the previous study (Creim et al, 1993) was not due to gastrointestinal (GI) bodily distress. The authors conclude that external stimulation of the body hair mediates the avoidance behavior of electric fields by rats (Creim et al, 1995).

Research examining function of the nervous system and the heart has also produced mixed results. No effects were found on neurotransmitters (chemicals in the brain responsible for nerve transmission) in rats exposed for up to 66 hours to dc electric fields of 3 kV/m (Bailey and Charry, 1987). Changes in brain wave (EEG) activity have been reported at 10 kV/m following a 90 minute exposure, but these changes may simply represent the animals' perception of the field from stimulation of their fur (Lott and McCain, 1973). In the same study, no changes in respiration or electrocardiogram (ECG) activity were reported at 10 kV/m.

Respiratory Function

Little research has focused on dc electric fields and respiratory function. However, progress of respiratory disease in mice (influenza) was reported not to be affected by dc electric field exposures up to 6 kV/m for 11 days (Krueger et al, 1970, 1974).

Reproduction and Development

The effects of electric fields on reproduction have been investigated in a single study of reasonable quality. Fam (1981) exposed mice over two generations to very strong dc electric fields (340 kV/m) for up to eight months. No effects on the number of born or surviving young were found (Fam, 1981). In this same study, microscopic examination of various organs, blood cell counts, and growth in these offspring revealed no adverse effects of dc field exposure.

4.3 HUMAN STUDIES

In laboratory studies of humans, research has focused on heart rate, blood pressure, and task performance during dc electric field exposure. As in the animal work, some studies report small, measurable responses to dc electric fields, while other studies do not.

For example, one study reported that maximum blood pressure and heart rate decreased during exposure to a dc electric field of 10 kV/m (Cassiano et al, 1965), while another reported no effect on either in a 30 kV/m field (Krivova, 1973). The disparity in these results may arise from the fact that the reported changes were very small (up to 9%), well within normal minute-to-minute variations in cardiovascular function. If electric field exposure did cause a very small effect, it would therefore be difficult to detect reliably, and moreover, such small changes would have no health impact.

Human performance also seems not to be affected by electric field exposure in any significant way. A study of volunteers exposed to a field of 1.4 kV/m for 6 hours per day for 30 days suggested that the exposure increased attention to tasks (Jones, 1974). However, in a different study, reaction time, a measure that is closely related to alertness and attention, was found to be unaffected in participants exposed to a 30 or a 60 kV/m field for 2 hours per day for 60 days (Krivova et al, 1973).

4.4 SUMMARY: DC ELECTRIC FIELDS

There is no mechanism to explain how exposure to external static electric fields could produce adverse biological responses. The fields induced within the body are negligibly small. Some laboratory studies have reported some behavioral responses, others have not. It is unclear from the design of some of the studies whether reported effects are due to field exposure rather than artifacts. The database of studies is small. The experiments overall do not indicate a clear pattern of effect, and provide no basis to conclude that exposure to electric fields, such as those associated with the electric field of a HVDC transmission line pose health risks.

5. DC MAGNETIC FIELDS

Magnetic fields are the third major component of the electrical environment around a dc line. The current in the conductors of an HVDC transmission line produces a steady magnetic field, much like the Earth's natural magnetic field. However, the magnetic field strength at the edge of right-of-way of an HVDC line changes the Earth's magnetic field approximately 10%. This is illustrated in terms of compass deflection in Figures 10.12, 10.13, 10.14. Beyond the right-of-way boundaries, the magnetic field from an HVDC line rapidly decreases to ambient levels (Figure 2.3 and Figure 10.11).

Even though the intensity of the magnetic fields associated with dc transmission lines is small in comparison to the Earth's geomagnetic field, there are several important reasons to evaluate the literature on dc magnetic fields. First, static magnetic fields, at intensities much greater than those associated with dc transmission lines, have been studied extensively, partially because of their use in medical diagnostics, such as magnetic resonance imaging (MRI), and this has raised some concerns. Second, the public's main focus of concern about transmission lines involves magnetic fields, albeit ac magnetic fields. Third, a change in the intensity and/or orientation of the Earth's magnetic field has been reported to affect orientation or navigational clues that are used by some animals. Fourth, although the strength of the dc magnetic field produced by the HVDC lines is comparable, to or less than, the geomagnetic field and thus unlikely to cause biological responses by itself, there are some theories that predict that the ac magnetic fields only produce biological or even harmful effects only in conjunction with dc magnetic fields of specific intensity and orientation. If these theories -- known as resonance theories -- were confirmed, even a minor change in the ambient magnetic field may produce biological responses.

5.1 MECHANISMS OF INTERACTION

Static magnetic fields interact with living tissue by a number of mechanisms, including those involving electrodynamic, magneto mechanical, or atomic and subatomic forces. Electrodynamic effects involve the interaction of magnetic fields with electrolyte flows, leading to the induction of electrical potentials and currents. These have been measured in the aorta and the heart as well as specialized organs.[3] Magneto mechanical effects involve the orientation of macromolecular assemblies in homogenous fields, and the translation of paramagnetic or ferromagnetic molecular species in strong gradient fields. Another type of interaction of static

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[3] This can occur in an organism with specialized organs, such as in the elasmobranch fish. An example of the magnetically induced electrical potentials in a biological system is the geomagnetic direction finding mechanisms used by elasmobranch fish, including the shark or skate. These fish have canals known as the ampullae of Lorenzini, which have electrical conductivity similar to seawater. When the fish swims through the geomagnetic field, a voltage gradient is induced in the canals, which is detected by the sensory epithelia in the ampulary region.

fields with tissue occurs at the atomic or subatomic level. Magnetic fields have been shown to influence certain chemical reactions, such as the free radical reactions, and these potentially could influence biological reactions as well. However, none of these mechanisms is known to be applicable to static magnetic fields at intensities associated with an HVDC transmission line.

5.2 ANIMAL STUDIES

The effects of static magnetic fields on many biological processes have been examined in animals. Research on genetic effects, cell growth, reproduction and development, and directional orientation and behavior are described below.

Genetic Effects

A number of studies have examined whether exposure to static magnetic fields produces chromosomal damage. Although a few reports have noted some effects of high intensity magnetic fields, overall the data does not support the conclusion that static magnetic fields induce genetic damage. The lack of cytogenetic effects of magnetic field exposure has also been reported in human lymphocytes exposed to magnetic fields of various intensities over various exposure times (Wolff et al, 1980; Cooke and Morris, 1981; Mileva, 1982; Peteiro-Carrtelle and Cabezas-Cerrato, 1989; Takatsuji et al,1989). For example, Peteiro-Carrtelle and Cabezas-Cerrato exposed human peripheral lymphocytes to magnetic fields of 450-1250 G for 3 hrs or 72-96 hrs. They observed no effects on chromosome aberrations or frequency of Sister Chromatid Exchange (SCE). One report (Takatsuji et al, 1989) did report a genetic effect of exposure to magnetic fields at 110 G on lymphocytes in conjunction with co-exposure to ionizing radiation. There was no response to magnetic fields alone, however. A review of the literature on genetic effects concluded: "The overwhelming preponderance of the evidence suggests that neither static nor ELF electric or magnetic fields have demonstrated a potential to cause genotoxic effects" (McCann et al, 1993).

Cell Growth

Several well-controlled studies of growth of various cell types exposed to strong dc magnetic fields show no robust or consistent responses on cell growth (Halpern and Green, 1964; D'Souza et al, 1969; Chandra and Stefani, 1979; Tsutui, 1979; Sandler et al, 1989; Hiraoka et al, 1992; Sato et al, 1992; McDonald, 1993). In one study, Malinin reported that high intensity magnetic fields transformed cells in culture and caused growth inhibition (Malinin, 1976). The techniques used in this study were flawed. Frozen cells were exposed to magnetic fields and then exposed cultures were passaged infrequently and then compared to frozen control cultures. Thus, it is not surprising that the results of Malinin have not been supported by subsequent research which attempted to replicate this study using more appropriate methods (Frazier et al, 1979).

Reproduction and Development

A number of studies have been performed to investigate a role of dc magnetic field exposure in development. In the study of Sikov et al (1979), pregnant mice were exposed or sham-exposed to a uniform field of 10 G or to a gradient (25 G/m) field with a maximum flux density of 10 G, either for the whole or part of gestation. Prenatal surveys of skeletal or internal malformation were done on day 18 of gestation. No differences were observed, though the number of fetuses scored was small. They did not report any differences in developmental landmarks or number of pregnancies or implantation rates. Other reports on mammalian development indicated no adverse effects from magnetic exposure less than 10 G (Mahlum, 1979; Konerman and Monig, 1986). These field intensities are about 1,000 fold greater than those associated with HVDC transmission.

Directional Orientation

Research also has attempted to determine how animals, particularly birds, respond to small changes in the intensity of the Earth's magnetic field. The Earth's geomagnetic field has been shown to influence the behavior and orientation of a variety of organisms ranging from bacteria to homing pigeons (Kirschvink, 1982). 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, 1980). Higher organisms have also demonstrated a sensitivity to the Earth's dc field. For example, homing pigeons have a magnetic compass sense and honeybees perform a waggle dance oriented to the Earth's magnetic 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 magnetite has been described for a number of species including birds, bees, bacteria, and recently humans. To date, Kirschvink and co-workers are the only investigators that have observed magnetite in humans (Kirschvink et al, 1992). Many questions are still unanswered about the role of magnetite in the detection of magnetic fields.

Behavior:Circadian Rhythms and Pineal Gland

An area of considerable interest consists of the study of possible responses of the nervous system's "biological clocks" to magnetic fields. It is well-known that many physiological, biochemical and behavioral parameters vary in a predictable fashion throughout the day. The pattern of these variations during a day are called circadian rhythms. Control over circadian rhythms is exercised by both internal and external factors. As for external factors, there are a limited number of factors known to influence circadian rhythms and these include light, feeding, and social interactions. Circadian rhythms can affect metabolic, endocrine, and behavioral systems. An important modifier of circadian rhythm is the hormone melatonin, which is produced by the pineal gland.

Semm and co-workers reported that a reversal of the vertical magnetic field component of the Earth's static dc magnetic field results in a reduction in electrical activity of the guinea pig pineal gland (Semm et al, 1980). Within a few years, this finding was confirmed by Reuss et al (1983) for a reversal of the horizontal component of the Earth's magnetic field. Such changes in electrical activity appear to parallel the reduction in melatonin synthesis in animals acutely exposed to a reversed horizontal component of the Earth's geomagnetic field. Furthermore even a change as small as 15 degrees in the inclination of the field was reported to be effective. Over the ensuing years, a large body of data has been assembled that indicates that these responses to alterations in dc magnetic fields depend upon intact photoreception by the eyes. In fact, some of the data have been interpreted as showing that a magnetic field 'receptor' also exists in the eye (Olcese et al, 1985). For example, magnetic field exposure during total darkness (Reuss and Olcese, 1986) abolishes the ability of the dc magnetic field exposures to affect melatonin levels.

Several studies have reported that reversals or other changes to the Earth's dc magnetic field for short durations during the night inhibit melatonin secretion and other aspects of pineal metabolism in whole animals (*in vivo*) [Lerchl et al, 1990; Lerchl et al, 1991; Yaga et al, 1993] and even in cells on plastic (*in vitro*) [Reiter et al, 1991]. However, only the melatonin secretion of albino rats, albino gerbils, and hypopigmented Long-Evans are reported to be affected by dc magnetic fields. The pineals of pigmented rodents such as gerbils (Stehle et al, 1988), Richardson's ground squirrel, and ACI rats are reported to be unresponsive to dc magnetic field stimuli (Olcese, 1990). Therefore, the response of the pineal gland to dc magnetic field stimuli appears to be quite species specific.

5.3 HUMAN RESEARCH

The question of potential adverse health impacts of ac power lines is fueled by the residential epidemiology studies of ac magnetic fields and to a lesser extent by studies of occupational exposures to electric and magnetic fields. Unlike the research with ac magnetic fields, there are no residential epidemiology studies that have examined the associations between estimates of exposure to dc magnetic fields and cancer. However, a handful of occupational studies have examined exposures to dc magnetic fields in relation to adverse health outcomes, and these studies are summarized below.

Two epidemiology studies have analyzed the health of workers exposed to strong magnetic fields. Marsh et al (1982) conducted a cross-sectional study of workers involved in operations to extract magnesium from magnesium chloride, or to extract chlorine and sodium hydroxide by electrolysis of brine in mercury or diaphragm cells. Although they reported some minor variations in some hematological parameters, overall, this study did not indicate that exposure to fields had adverse effects on general health. The other study focused on individuals who worked in U.S. national physics laboratories near devices with strong magnetic fields (Budinger, 1992). The results of this cross-sectional study were presented in summary fashion, so the design and analysis could not be completely evaluated. The reported results show no significant increase or decrease in the prevalence of 19 categories of disease among control and exposed workers.

Other investigators have studies various health endpoints of workers at aluminum reduction or chloralkali plants (Milham, 1979; Rockette and Arena, 1983; Barregard, 1985; Mur et al, 1987; Davis and Milham, 1993). Some of these studies report that workers in the aluminum industry have a statistically elevated mortality from leukemia. However, the production of aluminum involves exposure to many chemicals, some of which are known to be carcinogenic. These studies frequently did not measure either the intensity of magnetic fields to which the workers were exposed, nor provide a method for distinguishing the effects of magnetic fields from chemical exposures.

Although the number of database or epidemiology studies is small and the studies of weak design, the data do not allow one to conclude that exposure to dc magnetic fields affects health.

5.4 "RESONANCE" THEORIES

For many years, scientists have attempted to identify biological responses to ac magnetic fields at environmental levels. Several investigators have proposed theories that predict that ac magnetic fields are only biologically active in the presence of dc magnetic fields of specific intensity and orientation. For this reason, a discussion of these theories -- known as resonance theories follows below. In this chapter, both animal and human studies are discussed together.

<u>Ion Cyclotron Resonance (ICR)</u>

The ICR theory involves the effect of ac and dc magnetic fields on biological ions, such as Ca^{++}, Mg^{++}, K^{+} under "resonance" conditions. The theory was derived by physicists to explain the behavior of charged particles in cyclotrons where they are accelerated in a vacuum until they attain very high energies. Until recently, the resonance theory had not been applied to biological systems.

Drs. Liboff and McLeod have suggested that the three key components of the ICR theory (charged ions, an ac magnetic field and a dc magnetic field) are present any time that a biological system is exposed to ac magnetic fields, such as from electric power facilities (e.g., McLeod and Liboff, 1986, 1987). The Earth's own geomagnetic field provides the necessary dc magnetic field, and ions are an important constituent of all body fluids and tissues. However, the vast majority of the laboratory data in support of the experimental predictions of the ICR theory made by Drs. McLeod and Liboff, comes from their own laboratories (e.g., see the summary in Liboff et al, 1990; Figure 5.1). There are serious theoretical objections to resonance theories because they are inconsistent with known physical principles (Durney et al, 1988; Halle, 1988; Sandweiss, 1990).

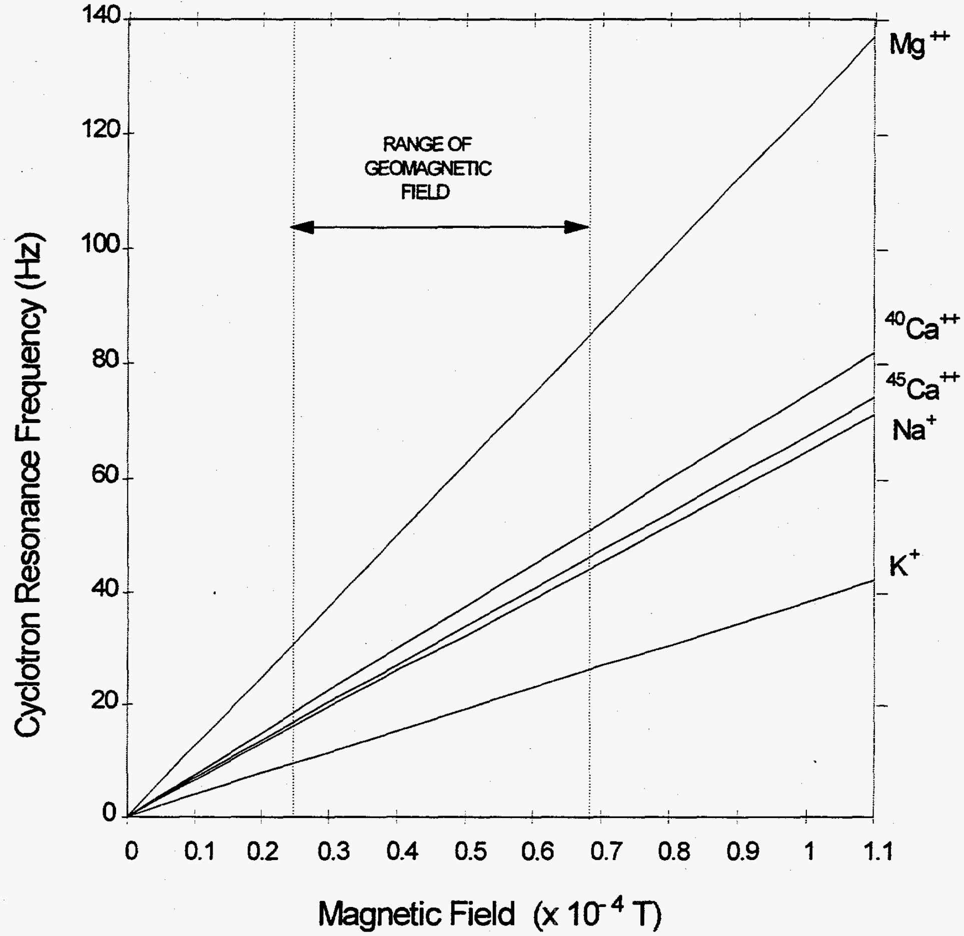

Figure 5.1 Cyclotron resonance (CR) frequency as function of magnetic field for various ions. Range of Earth's magnetic field (total intensity) over the earth's surface is superposed. (Liboff, et al, 1987)

An example of experiments testing the ICR theory involves biological responses of the single-celled marine diatoms to combined ac and dc exposures. These investigators reported that exposure of diatoms to dc and ac magnetic fields tuned to the ICR condition for Ca^{++} resulted in an increase in diatom mobility (Smith et al, 1987a,b; McLeod et al, 1987a,b). They infer that the observed biological responses under ICR conditions result from changes in transport through transmembrane ion channels. However, attempts at careful replication with attention to experimental detail have failed to confirm the original experimental reports on diatoms or other experiments based on ICR (e.g., see Reese et al, 1991; Prasad et al, 1991; Parkinson et al, 1992). Furthermore, all direct tests of possible involvement of transmembrane ion channels under ICR conditions that have been performed to date have been uniformly negative (see Durney et al, 1992; Breger and Blumenthal, 1992; Galt et al, 1993).

Lednev (1991) has proposed a new theoretical mechanism which also involves—like ICR theory—the simultaneous presence of a dc magnetic field and an ac magnetic field. Lednev proposes that an ion will have the energy level of its outer shell electrons "split" into two levels as a result of the presence of the dc magnetic field (this splitting is known from classical physics as the splitting or the Zeeman effect). He predicts that this affects the binding of charged ions to proteins, and hence biologic activity.

Lednev's model has been further refined by Drs. Blanchard and Blackman (Blackman et al, 1994; Blanchard et al, 1994). The ion parametric resonance (IPR) model corrects mathematical errors in the Lednev model and extends the model to predict the probability that an ion shifts to a different energy level near resonance. Unlike other resonance models, this model predicts that biological responses will vary with the intensity of B_{ac}, in a Bessl function and that increases and decreases in responses may occur at specific intensities of B_{ac}. The relevant biological responses are assumed to be alterations in enzymatically controlled reactions where ions serve as co-factors.

Drs. Blanchard and Blackman have tested this theory by exposing PC-12 cells[4] incubated with nerve growth factor to specific combinations of alternating and static fields and observing the frequency of cells exhibiting neurite outgrowth. The agreement between predicted and experimental values was poorest for low B_{ac}/B_{dc} ratios. In *post hoc* analyses, this agreement was improved considerably by assigning a special role to hydrogen ions as trigger ions. When the static field was adjusted to 20 mG to produce an "off resonance" condition, similar variations in B_{ac} relative to B_{dc} did not inhibit neurite outgrowth.

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4 A cell in culture, derived from the neural crest, that sprouts neurites under specific conditions in culture. The development of neurites has been used as a marker of differentiation.

Potential Relevance of Resonance Theories to Real World Conditions

Much of the literature on health effects of ac fields has been difficult to replicate, both in the epidemiologic studies and in laboratory studies. Advocates of ICR theory have proposed that the weak and inconsistent nature of the data to date is the result of the wrong exposure metric for magnetic fields having been used. If the "correct" (i.e., ICR theory-derived) metric were to be used, they believe that the epidemiologic data would be strong and consistent. Three recent reports using slightly different approaches have attempted to determine if measurements of dc magnetic fields can help interpret or design the epidemiologic data concerning ac power lines. The first report proposes an exposure metric using combinations of ac/dc fields (Blackman and Most, 1993). The second report re-analyzed data from an epidemiologic study of ac power lines by taking into account the dc magnetic field (Bowman et al, 1994). The third paper recommended parameters that should be considered when designing epidemiologic studies (Liboff and McLeod, 1995).

Blackman and Most (1993) hypothesized that an exposure metric based on a resonance model involving specific ac/dc combinations would improve the validity of the epidemiologic data studies of ac field sources. Blackman and Most developed an exposure rating system proposed for use in epidemiologic studies, based on their interpretation of observations reported in laboratory studies. The data they selected were *in vitro* studies on release of calcium ions from chicken brains and other tissue. These data were assumed to indicate "effective laboratory frequencies" for the calcium-ion release phenomenon at specific dc magnetic field intensities.

Unfortunately, Blackman and Most's theory is based on too many assumptions. These include: 1) the data used to estimate model parameters are valid; 2) the effects observed, even if valid, are relevant; 3) the effects would occur in human tissues *in vivo;* and 4) the effects are connected to cancer or any other human disease. There is no consensus in the scientific community that the release of calcium ions from chick brains or other tissues after ac and dc exposure is 'real.'

The paper by Bowman et al (1994) provides an equation specifying that for any given frequency of an ac magnetic field, a response is predicted for a very small range of intensities of a dc magnetic field. Bowman and co-workers applied this theoretical equation to analyze data from the published study of London et al (1991). London et al reported that children with leukemia (cases) living in the Los Angeles area were more likely to have power lines outside the home (almost entirely low voltage distribution lines) with a higher rated capacity to produce magnetic fields at the residence than healthy (control) children. However, when the exposures of the cases and controls were compared based upon measured ac electric or magnetic fields within the residence, no differences in exposure were found. The level of the dc magnetic field also measured in the residence did not differ between cases and controls.

Bowman et al compared the exposures of cases and controls to estimates of 60-Hz magnetic field levels within two ranges of dc magnetic fields (330-420 mG and 460-550 mG) centered about the calculated resonance values. They reported no trend for cases to be exposed more frequently to higher 60 Hz fields (estimated from either wiring codes or 24-hr average measured magnetic) if the dc magnetic field in the residence fell outside the 330-420 mG band. Within this band, however, cases appeared to be more frequently exposed to higher estimated 60 Hz magnetic fields, but the numbers were small. When Bowman et al conducted a similar analysis on residences occupied for 50% of the time since conception, no such trend was evident.

In the other band of dc magnetic fields between 460 and 550 mG, no difference in exposures of cases and controls were noted. This is inconsistent with the Bowman hypothesis, which predicts effects in both ranges of dc magnetic fields. Bowman et al have hypothesized that the risk of childhood leukemia is related to certain combinations of 60 Hz and dc magnetic fields. This paper examining the hypothesis contains speculation, not definitive evidence.

A paper just published by Liboff and McLeod (1995) proposes that an exposure metric based on the ICR theory be applied in the design or reinterpretation of epidemiologic studies. The model incorporates aspects of an ac field from a powerline, and the geomagnetic field that they propose are relevant. This model assumes very specific ICR conditions, and simple powerline conditions. One disadvantage of this model is that it is too idealized. It assumes that the geomagnetic intensity of a residence is solely influenced by the Earth's field, and likewise that the ac magnetic field intensity is solely derived from nearby power lines.

In addition to the theoretical limitations of resonance theories and the limited consistency of supporting data, applying this theoretical model in the 'real world' is extremely problematic. While in the laboratory you can carefully control the orientation and the intensity of the ac and dc fields, this is not possible in the real world. Recent measurements of the dc fields in residences (Swanson, 1994; Wong and Sastre, 1995) indicate that it is highly unlikely that ac and dc magnetic fields will be present at the various intensities and orientation that correspond to appropriate theoretical resonance conditions.

Both Wong and Sastre (1995) and Swanson (1994) report that dc magnetic fields are highly variable within the home. The variations were most dramatic near metallic or magnetic objects. For example, within a distance of one foot of a steel chair, the Earth's field changed by up to 60 mG. Swanson reported within the same home the dc field intensity in the bedroom was not correlated with the fields in the living room. These actual measurements raise questions about the potential relevance of the resonance theories to studies of people. The variations of dc field intensity in the home is much greater than the variations in dc field intensities allowed by the resonance conditions.

5.5 SUMMARY: DC MAGNETIC FIELDS

Studies of animals and humans do not indicate that exposures to dc magnetic fields up to 20,000 mG would result in adverse health outcomes. Avian or animal migration or behavior can be influenced by dc magnetic fields. While resonance theories have been proposed to explain effects of ac magnetic fields, the theoretical, experimental and practical support for these theories is weak. A proposed HVDC transmission line would perturb the Earth's field at the edge of the right-of-way less than many metallic objects or cars.

The magnetic field at the edge of a typical right-of-way of an HVDC transmission line in North America will be at most 10% higher or lower than the magnetic field of the Earth. For this reason alone, it seems unlikely that this small contribution by HVDC lines to the background geomagnetic field would be a basis for concern. However, public concern over the siting of ac power lines and ac magnetic fields necessitates that a scientific evaluation of dc magnetic field be provided to differentiate dc from ac public health issues. A brief discussion of research on ac magnetic fields is included as an appendix.

6. WILDLIFE AND PLANTS

A few studies have been conducted to assess the potential effects of exposure to electric and magnetic fields associated with high voltage dc transmission lines on individual biological organisms; few studies have evaluated effects on whole ecological communities. This is unfortunate because an adverse impact upon an individual species may not seem important when considered isolated by itself, but in the context of an ecological community, the loss or decline of one keystone species can have a cascading effect on other directly or indirectly associated species. For example, a decline in honeybees could lead to a decline in the plant species they pollinate. In turn, a decline in these plant species may lead to a decline in the amount of forage available to herbivores, thus leading to their decline.

The impacts of construction and maintenance of ac and dc transmission line rights-of-way, should be similar. Since the dc environment has distinct electrical characteristics, the potential effects on wildlife and plants are distinct from those of ac environments. There have been four field studies which have examined the potential ecological impact of dc transmission lines. One of these studies was described in the chapter on air ions (see Chapter 3, Angell et al, 1990), another in a discussion of air quality (Krupa and Pratt, 1982) and the other two studies are described below. Also, in this chapter the potential impact of the distinct aspects of the electrical environment (air ions, dc magnetic fields, dc electric fields) on plants and wildlife are reviewed.

Genereux and Genereux (1980) described the perception of farmers near a +/- 400 kV dc powerline in West Central Minnesota. This survey study indicated that 31 percent or 119 out of 384 respondents believed that the powerline affected the wildlife under or near the line. Seven percent complained that wildlife were gone from the area; 14 percent that the wildlife avoided the area under the line, and 5 percent that birds had been killed by the line. This survey is anecdotal in nature and potentially biased by widespread opposition of farmers to this transmission line.

Griffith performed a study to investigate the effect of the Celilo-Sylmar +/-400 kV transmission line in Oregon on the plant and animal communities (Griffith, 1977). He performed systematic sampling of these populations with primary emphasis on crops, natural vegetation, songbirds, raptors, small mammals, pronghond 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. Some examples of species affected by the transmission structure include: robins, Brewer's sparrows or pinon mice. Those species that were positively affected used the transmission line structures as part of their feeding, hunting or resting habitats. Some examples of species positively affected by the transmission structure include some types of raptors and Townsend's ground squirrels. The impacts of the 400 kV transmission line that were observed were believed to be related to the construction of the line, rather than the electrical environment associated with the line. However, it is not possible from this study alone to dismiss the possible impact of electric fields.

6.1 AIR IONS

A substantial amount of laboratory research had been performed on the effect of exposure of plants to air ions. The research examining the effects of air ions on plant growth, like that associated with air ion research on animals and humans, consists of a few observations 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 significant increase in dry weights of plants (Krueger, et al, 1962, 1963). They reported that this increase was dose dependent when they exposed the plants to concentrations ranging from 0.5 - 1.3 x 104 ions/cm^3. Other workers, (Wachter and Widmer, 1976) found that plants grown in ionized air showed enhanced fresh weights along with enhanced growth, but no change in dry weights. An explanation for this observation is that the increase in growth was at the expense of the existing mass.

Seedlings of barley, when cultivated in an iron-deficient nutrient medium, eventually develop an iron chlorosis, and when pre-chlorotic plants were cultivated in an atmosphere of air ions, either positive or negative, it was reported that the onset of chlorosis was accelerated markedly with a simultaneous increase in the cytochrome c content. (Krueger et al, 1963, 1964). These findings supported evidence that an important enzyme of cellular respiration, cytochrome c, is a chief mediator for the biological action of air ions. However, it must be kept in mind that without information about changes in the levels of unrelated cellular proteins, it is not possible to draw conclusions about respiratory proteins or whether many or all other cellular proteins increase as well.

6.2 ELECTRIC FIELDS

Most wildlife are shielded from electric fields by surrounding vegetation. Thus, small ground dwelling species such as mice, salamanders, and snakes are usually shielded from electric fields. In addition, organisms which live underground, such as moles and woodchucks, are totally shielded from electric fields by the soil. Hence, only large wildlife species, such as deer and moose, have potential exposure to electric fields, since they can stand taller than surrounding vegetation. However, the duration of potential exposure for deer and other large mammals is likely to be limited to foraging bouts or the time it takes them to cross under the line.

Some studies were performed to examine the effect of electric fields on plants. An experimental test facility was designed to examine possible effects of a +/- 100 kV dc powerline upon growth of wheat plants positioned at three heights under the +100 kV and -100 kV test lines (Endo et al, 1979). The field intensities were calculated to be 70 kV/m (without corona) and 19.5 kV/m (with corona). The investigators concluded that there were "no significant differences" between the control and exposed plant. A re-evaluation of the data suggested that their conclusions of no significant differences were questionable (Bailey et al, 1982). However, no further study or analysis was published.

6.3 MAGNETIC FIELDS

The studies performed on plants exposed to dc magnetic fields have predominantly focused on effects on genetic, growth and enzymatic activities. A few studies have been performed examining if any adverse genetic effects are associated with exposure to static fields (McCann et al, 1993). No adverse effects have been reported. There have been a few studies on the effects of fields on growth, but the results have been inconsistent (Simon, 1989).

6.4 CONCLUSIONS

Studies have performed both in the field and examining the isolated aspects of the electrical environment of HVDC line. None of the studies that have been performed to date indicate any adverse effects on plants or wildlife.

7. ASSESSMENT, COMPARISON AND CONCLUSIONS BIOLOGICAL IMPACTS - CHAPTERS 1-6

Most of the high voltage transmission in the world is in the form of high voltage alternating current (HVAC). However, with the proper equipment, ac can be converted to dc electricity. High voltage direct current (HVDC) transmission of power can be both more efficient and less costly for transporting large quantities of power over long distances. Chapters 1-6 of this report have reviewed the potential environmental and health impacts associated with exposure to the electrical environment of HVDC transmission lines. In this chapter, the conclusions of this assessment are summarized and the potential impacts of ac and dc transmission are compared.

The electrical environment of a high voltage transmission line can be characterized by three electrical parameters: the electric field, the air ion and charged aerosol concentration, and the magnetic field. The electric field arises from both the electric charge on the conductors and for an HVDC transmission line, charges on air ions and aerosols surrounding the conductor. In addition, corona may also produce low levels of ozone, audible noise, electric field and radio interference. HVAC and HVDC differ in these characteristics as well. All except the differences in ozone level are discussed in Chapter 10 of this report. A static magnetic field is produced by current flowing through the conductors.

7.1 AIR ION RESEARCH

Potential exposure to elevated concentrations of air ions occurs for an HVDC but not HVAC transmission lines. When air ions are produced by an HVAC transmission line, they are alternatively repelled and attracted as the polarity changes on the conductors. Therefore, air ions that are produced are attracted back to the conductors, and there is essentially no environmental exposure to air ions from ac lines. For an HVDC transmission line, air ions move away from conductors of like polarity and are attracted to the conductor of opposite polarity. Some air ions are carried away from the conductors and fall to the ground. Thus, in the vicinity of an HVDC line and for considerable distance downwind, exposure to elevated concentrations of air ions can occur.

Research on animals has focused primarily on short-term effects of behavioral and physiological indices of arousal, the metabolism of the neurohormone serotonin, and on the respiratory tract. In addition, effects of long-term exposures on reproduction and health have been assessed both in laboratory rats and in cattle living under or near operating HVDC transmission lines. However, most animal studies failed to properly control and measure air ion exposures as well as other important environmental factors. Even so, the responses reported in animal studies are often small in magnitude although the exposures are often many fold greater than could be found in the vicinity of HVDC transmission lines.

Research on human subjects to a large extent parallels the research on animals. Effects on mood and performance, serotonin metabolism, and the respiratory system have been studied. The problems of measuring and controlling exposures in human experimental studies are similar to those observed in animal studies. Several health surveys of persons living adjacent to HVDC transmission lines have not reported a greater prevalence of acute health complaints, e.g., headaches, respiratory congestion, than among persons living away from the lines.

Neither the animal nor human studies provide any reliable evidence for the proposition that air ions produce any harmful effects. In fact, there is considerable uncertainty as to whether there are any biological responses to air ions. At the levels produced by HVDC transmission lines, the possibility of risk to human health appears remote, if not vanishingly small.

7.2 ELECTRIC FIELDS

There is no mechanism to explain how exposure to external static electric fields could produce adverse biological responses. The database of studies is small. The experiments overall do not indicate a clear pattern of effect, and provide no basis to conclude that exposure to electric fields, such as those associated with the electric field of a HVDC transmission line, pose health risks.

7.3 MAGNETIC FIELDS

Studies of animals and humans do not indicate that exposures to dc magnetic fields up to 20,000 mG would result in adverse health outcomes. Avian or animal migration or behavior can be influenced by dc magnetic fields. The magnetic field at the edge of a typical right-of-way of an HVDC transmission line in North America will be approximately 10% higher or lower than the magnetic field of the Earth. For this reason alone, it seems unlikely that this small contribution by HVDC lines to the background geomagnetic field would be a basis for concern. While resonance theories have been proposed to explain how of ac magnetic fields might produce biological responses only in conjunction with dc magnetic fields of appropriate orientation and intensity, the theoretical, experimental and practical support for these theories is weak.

In contrast to the studies on dc magnetic fields, the studies on ac magnetic fields have been more controversial. In fact, public concern over the siting of ac power lines focuses on ac magnetic fields. To date, the scientific research has not allowed one to conclude that exposure to ac magnetic fields is associated with any adverse health effects. However, the research on ac magnetic fields is much more complex and raises more questions than the research with dc magnetic fields.

Table 7.1

HVAC VERSUS HVDC: POTENTIAL HEALTH IMPACTS OF ELECTRICAL ENVIRONMENT		
	AC	**DC**
Air Ions	**Not relevant**	**No observed effects**
Electric Fields	**No observed effects**	**No observed effects**
Magnetic Fields	**No cause & effect Research is continuing**	**No observed effects**

8. REGULATIONS AND GUIDELINES REGARDING ELECTRIC AND MAGNETIC FIELDS

Over the past 15 years, there have been numerous reviews of the scientific literature on static magnetic and/or electric fields for scientific or regulatory organizations. These have included evaluations performed by the World Health Organization (WHO), the Lawrence Livermore Laboratory, the Food and Drug Administration (FDA), American Conference of Governmental Industrial Hygienists (ACGIH), the National Radiological Protection Board (NRPB) of Great Britain and the European Committee for Electrotechnical Standardization (CENLEC). Although, each of these organizations has recommended regulations or guidelines to limit human exposure to magnetic fields, most of the exposure limits are hundreds to thousands times higher than fields associated with HVDC transmission lines. Some organizations have proposed guidelines for electric fields as well, but the recommended levels are much closer to levels associated with HVDC transmission lines. No regulations or guidelines have been proposed to limit exposure to air ions.

8.1 LAWRENCE LIVERMORE NATIONAL LABORATORY

Lawrence Livermore National Laboratory (LNLL) developed exposure guidelines for static magnetic fields to protect their personnel who worked near strong magnetic fields from magnets in fusion reactors. These guidelines limit whole body exposure to a time-weighted-average (TWA) field strength of 600 G over a 24 hour period. The 600 G limit is based on the average voltage generated in blood; An ionized fluid, like blood, moving in a static field generates voltage by magneto hydrodynamic (MHD) forces. LNLL also recommends that workers not be exposed to peak fields exceeding 20,000 G. The same limits are endorsed by ACGIH (1995)

8.2 FOOD AND DRUG ADMINISTRATION (FDA)

The Center for Devices and Radiological Health of the Food and Drug Administration has issued guidance to manufacturers submitting 510 (k) applications for review of magnetic resonance (MR) diagnostic devices in accordance with 21 CFR 807.87. Safety concerns are below the level of regulatory concern if the static magnetic field is less than 20,000 G and the dB/dt is less than 6000 G/second. There also is a required labeling guideline for MR devices that might possibly expose persons with cardiac pacemakers or other implanted electronic devices to static magnetic fields exceeding 5 G (0.5 mT). Evaluations of other devices producing electromagnetic fields are not assessed with respect to formally established guidelines, but rather are assessed on a case-by-case basis.

8.3 NATIONAL RADIOLOGICAL PROTECTION BOARD (NRPB)

In 1993, the National Radiological Protection Board (NRPB) published a statement recommending restrictions on human exposures to static electromagnetic fields (NRPB, 1993). The recommendations are based on assessments of human health information from laboratory studies, dosimetric data, and epidemiology. The restrictions do not distinguish occupational exposures from exposures for the general public. For electric fields, they concluded:

> *There is no biological evidence from which basic restrictions on human exposure to static electric fields can be derived. Guidance is limited to the avoidance of the effects of surface charge. For most people, the annoying perception of surface electric charge, acting directly on the body, will not occur during exposure to static electric field strengths of less than about 25 kV/m.*

For static magnetic fields the NRPB concluded:

> *Acute responses will be avoided if exposure is limited to fields of less than 2 T (20,000 G). In view of the uncertainties associated with chronic exposure, and the lack of information on human exposure to fields of this magnitude, it is considered appropriate to restrict the time weighted exposure over any 24 hour period to 200 mT (2,000 G), which represents one-tenth the threshold for acute responses.*

8.4 INTERNATIONAL COMMISSION ON NON-IONIZING RADIATION PROTECTION (ICNIRP)

Guidelines on static magnetic fields have been proposed by the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 1994). ICNIRP was established as a continuation of the former International Non-Ionizing Radiation Committee of the International Radiation Protection Association (INIRC/IRPA). INIRC/IRPA, in cooperation with the Environmental Health Division of the World Health Organization (WHO), had previously developed guidelines in 1991. The ICNIRP directive is to investigate hazards that may result from non-ionizing radiation and to protect the public. In reviewing the data on static magnetic fields, the committee concluded:

> *Current scientific knowledge does not suggest any detrimental effect on major developmental, behavioral and physiological parameters in higher organisms for transient exposure to static magnetic flux densities up to 2 T (20,000 G).*

In determining the guidelines for exposure, a distinction was made between the general public and occupational exposure. The occupational exposure limits are overall less stringent than for the general population because the exposures are controlled, the population exposed is adult, and these people usually receive specific training for their jobs. The exposure limits for the general public and the occupational situations are shown in Table 8.1. The recommended occupational exposure limit is 2,000 G. The recommended exposure limit for the general public is even more conservative. For continuous exposure, a limit of 400 G was recommended.

ICNIRP recommended special consideration for magnetic field exposures of individuals with cardiac pacemakers and ferromagnetic implants. The majority of cardiac pacemakers are unlikely to be affected in fields less that 5 G and these individuals should avoid fields greater than 5 G. The advice for people with ferromagnetic implants (such as orthodontic magnets) was to avoid exposures greater than a few millitesla (few Gauss).

Table 8.1

LIMITS OF EXPOSURE TO STATIC MAGNETIC FIELDS	
Exposure conditions	**Magnetic Flux Density**
Occupational	
Whole working day (time-weighted average)	2,000 G
Ceiling value	20,000 G
Limbs	50,000 G
General public	
Continuous exposure	400 G

8.5 COMITÉ EUROPÉEN DE NORMALISATION ELECTROTECHNIQUE (CENELEC)EUROPEAN COMMITTEE FOR ELECTROCHEMICAL STANDARDIZATION

Most recently, CENELEC published the first standard limiting exposures of workers and the general public for use in 18 European countries. The standards have been presented in provisional form as a pre-standard authorized for a period of three years. Part 1 of the standard covers the frequency range of 0 to 10 kHz. This standard focuses on documented short-term responses to electric and magnetic fields.

The CENELEC exposure guideline is structured into two components as "Basic Restrictions," and as "Reference Levels." The basic restrictions are ceiling values based on induced current density, or field level that "shall not be exceeded." The basic restriction for whole body exposure to dc electric fields* is 42 kV m^{-1} (peak). For dc magnetic fields, the whole body exposure basic restriction is 20,000 G. These basic restrictions represent field levels that "shall not be exceeded." The reference levels, on the other hand, are field levels that alert the user to the need for further attention. The reference levels are field level values that, if exceeded, may indicate possible non-compliance with the basic restriction.

The reference levels for dc electric and magnetic fields are defined as peak field values. The CENELEC reference level for workers exposed to dc electric fields is 42 kV m^{-1}. A limit to the duration of exposure for workers is also given as: $t \leq 112 / E$ (where t is time in terms of hours, and E is electric field in terms of kV m^{-1}). The duration limit defines the total time the worker may be exposed above a particular field level within any 8-hour period. For example, at 0 Hz, the worker may be exposed to fields above 28 kV m^{-1} for no more than 112/28 = 4 hours. For workers, the reference levels for dc electric fields may be exceeded provided that adherence is maintained for the duration limit, basic restriction, and where the field orientation is predominantly perpendicular, rather than parallel, to the body. The reference level for dc electric field exposure of the general public is 14 kV m^{-1}.

The CENELEC reference levels (peak) of whole body exposure of workers to dc magnetic fields is 20,000 G. The pre-standard also specifies an 8-hour time-weighted-average (TWA) limit of 20,000 G for workers. For the general public, the reference level for whole body exposure to dc magnetic fields is 20,000 G. Higher exposure is permitted to the limbs because they do not contain critical organs. The dc magnetic field reference levels for exposure to the limbs of workers and the general public are 5 T and 0.1 T, respectively.

8.6 AMERICAN CONFERENCE OF GOVERNMENTAL INDUSTRIAL HYGIENISTS (1995-1996)

The American Conference of Governmental Industrial Hygienists (ACGIH) routinely develops guidelines to assist in controlling exposures to potential health hazards in the workplace. The guidelines are designed to ". . . represent conditions under which it is believed that nearly all workers may be exposed day after day without adverse health effects." The policy statement of the ACGIH states that these guidelines or Threshold Limit Values (TLVs) are intended for use by trained individuals, and should not be regarded as a fine line between safe and dangerous levels."

THE ACGIH did not find support to conclude that exposure to static fields poses a serious health risk. The guidelines are based on limiting currents on the body surface and induced internal currents to levels below those that are believed to produce adverse health effects. For static magnetic fields routine occupational exposure should not exceed 600 G for the whole body and 6000 G for the extremities on a daily, time-weighted average basis. A flux density of 20,000 G is recommended as a ceiling value. For static electric fields, occupational exposures should not exceed a field strength of 25 kV/m. At this time, they concluded that there is insufficient information on human responses and possible health effects of electric fields in the static range to permit the establishment of a TLV for time-weighted average exposure. Therefore, the electric field intensities are root mean square (rms) values.

8.7 MINNESOTA AND NORTH DAKOTA STATE ELECTRIC FIELD GUIDELINES

Although neither state has engaged in formal rulemaking, both states have imposed limits on maximum dc electric fields for the CPA/UPA ± 400 kV transmission line when they certified the line in 1976 (Banks et al, 1977). The limits are not based upon assessments of health risks. In Minnesota, the limit is 12 kV/m, but this applies only to the static electric field with out the electric field component contributed by space charge (air ions and charges aerosols). The North Dakota Public Service Commission, however, limited the electric field to the estimated maximum that would occur for monopolar operation, 32 kV/m. This was cited as being below a field level of 40 kV/m where a person wearing commercial footwear would seldom experience any sensation.

9. PUBLIC PERCEPTION AND SITING ISSUES

In the 25 years following the building of the first HVDC transmission line in North America, only a handful of HVDC transmission lines have been constructed. One of the major reasons why more lines have not been built is the relatively high cost of AC/DC power conversion. If this hindrance is overcome, more HVDC lines can be built. However, the ability to site HVDC lines will depend on public acceptance of these new facilities.

Since 1970, there has been public opposition to major high voltage ac transmission line projects. Most of the public opposition to construction of new ac power lines involves concerns about health. From 1970 to about 1985, these concerns focused on electric fields, but these were replaced by concerns about ac magnetic fields. The scientific research relating to potential health effects from the electrical environment of a HVDC transmission line is less controversial than for an HVAC line. Based on the science alone, one might predict that public acceptance of an HVDC transmission line would be easier than an HVAC transmission facility. This presumption, however, is based only a technical, scientific perspective. The purpose of this chapter is to discuss how public acceptance of new technology is based not on exposures and scientific facts, but is largely a function of perception.

9.1 HEALTH AND SAFETY CONCERNS ABOUT HVDC TRANSMISSION LINES IN THE U.S.

Although the siting of the first HVDC transmission line, the 1361 km +/- 400 kV Pacific Northwest-Southwest Intertie, that runs from Oregon to California, encountered no serious public opposition on health concerns, HVDC transmission lines subsequently proposed have encountered major public opposition based upon health concerns. This chapter provides summaries of the siting history of six HVDC projects proposed in the U.S. since 1970. No HVDC line has been sited in the US since the late 1980's. The history of the siting of these facilities has been varied. One facility was sited and constructed in spite of pubic opposition in a controversy that lasted more than 10 years and increased construction costs by $142 million. Three projects were sited and constructed only after health concerns were addressed in lengthy siting hearings or litigation; one project was canceled because of public and regulatory fear of air ions produced by HVDC transmission lines; and one project was sited and approved without major public concern about potential health impacts.

<u>CPA/UPA Transmission Line</u>

In 1973, the Cooperative Power Association (CPA) and the United Power Association (UPA) proposed to build a 692 km +/- 450 kV HVDC transmission line to bring power from a coal-fired power plant in Underwood, North Dakota to the twin cities of Minneapolis/St. Paul. By the time surveying for the line began in 1978, widespread public opposition to the line arose based on cost, environmental impact - including the value of rural life and agriculture, the siting process, land acquisition practices, and finally, health and safety concerns. In January, mass demonstrations occurred and state troopers were called in. Ultimately, a force of 300 security guards were added to prevent vandalism. In August 1978, the first of 12 towers was toppled by outraged farmers. Altogether, direct damages of $43 million were incurred, and the total cost of the controversy to the cooperatives was over $142 million. The threat to the line was so great that the line was deeded to the Rural Electrification Administration (REA), so the Federal Bureau of Investigation could be called in to provide additional protection. Over 120 persons were arrested in a two year period for criminal acts pertaining to protests.[5] Having exhausted all grounds for having the line moved or turned off, the main focus of the farmers' protests turned to health and safety. The state had unsuccessfully mounted several initiatives to address these concerns. Finally, in 1980, a blue ribbon panel of scientists was assembled to review all health and safety aspects of the operation of the CPA/UPA transmission line. Overt opposition diminished after the release of their report in 1982 which concluded "[t]here is now no scientific basis to believe that the electric and magnetic fields and air ions produced by the CPA/UPA +/- 400 kV dc powerline pose a hazard to human or animal health" (Bailey et al, 1982). Perhaps as persuasive to the farmers were the findings of a report from researchers at the University of Minnesota that the performance and health of dairy cows were unaffected by the operation of the line (Martin et al, 1983a). Of note, is the fact that a companion line, the +/- 250 kV Square Butte transmission line, was constructed from North Dakota to Minnesota to the north of the CPA/UPA transmission line within this same time period without substantial opposition.

<u>New England - Hydro Quebec Phase I</u>

In 1981, the Vermont Electric Transmission Company and New England Electric Transmission Co. applied for permission to construct a 84 km, +/- 450 kV transmission line from Norton, VT to a converter station located in Monroe, New Hampshire near Comerford Dam to serve as the Vermont portion of a proposed transmission interconnection between the Hydro-Québec and the New England Power systems. The Vermont Department of Public Service and the Department of Health conducted an extensive investigation of heath and safety issues associated with the project. Two studies were commissioned: one was a study of the effects of the electrical environment produced by an HVDC test line of the same design as that proposed; and the other was a health survey of a community residing near the Pacific Northwest-Southwest Intertie transmission line in Sagus, California to address concerns about air ions (See discussion of Nolfi and Haupt, 1982 on p. 23). In spite of these efforts, concerns about potential health effects of the proposed transmission line were a central issue in the certification hearings. The line was approved in 1983 by the Public Service Commission, and became operational in 1986.

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[5] The history of this protest has been described in a dramatic account as being "The First Battle of America's Energy War" involving confrontations between rural America and U.S. energy policies (Casper and Wellstone, 1981).

New England - Hydro Quebec Phase II

The New England Hydro-Transmission Corporation proposed to construct a 195 km, +/-450 kV transmission line from the Comerford HVDC Converter Station southward to the New Hampshire-Massachusetts border. New England Hydro-Transmission Electric Co. proposed a 19 km extension of this line from the New Hampshire border to a converter station located in Ayer, MA. Public opposition to the proposed line in both New Hampshire and Massachusetts developed based on concerns about potential health impacts of the electrical environment, and these were discussed among other issues in lengthy public hearings. As a requirement for certification, the New Hampshire Public Utility Commission required that the company monitor developments in laboratory research on dc magnetic fields and air ions for two years before and five years after the line became operational. A requirement to monitor the electrical environment around the line before and after construction was also imposed. The Energy Facilities Siting Board (EFSB) of Massachusetts required that the company evaluate alternative proposals to monitor the electrical environment and to evaluate the cost and feasibility of health surveillance studies. This transmission line has been in operation since 1990.

IPP Project

The Intermountain Power Project (IPP) involved the construction of a coal-fired generating plant in Delta, Utah, and the transmission of power on a 787 km, +/- 500 kV transmission line to Victorville, California near Los Angeles. Limited public concern arose, but a lawsuit was filed in federal court by the town of Henderson, NV et al. in 1983 that challenged the adequacy of the environmental impact statement as to the assessment of potential health impacts. The court ruled in favor of the defendants in 1984, and the line was energized in 1986.

Texas HVDC Transmission line

In 1983, three Texas utilities proposed to construct a 246 km +/- 400 kV HVDC transmission line between Walker County and Matagorda Station. The purpose of the line was to connect the Southwest Power Pool and the Electric Reliability Council of Texas based upon a need determination by the Federal Energy Regulatory Commission. Opposition to the transmission line quickly centered around the routing of the line and potential health effects. These issues coalesced for members of the public who were concerned about the routing of the line through a childrens' camp and conference center operated by the Episcopal Archdiocese of Texas for use by thousands of children, and a much larger group of persons for other purposes. In ruling on the application for a certificate of Convenience and Necessity, the hearing examiner concluded that despite extensive testimony "the health concerns associated with this line are so questionable that the need for the line cannot outweigh the possible negative health implication associated with it." The application was rejected since the examiner felt that the "Applicants had not met their burden of proof to show that this line will not adversely affect the health of those individuals who must live and work along this line . . ." (PUCT, 1984). Several years later, the applicants applied for and received permission to construct a back-to-back HVDC link involving no overhead transmission.

Mead-Phoenix Transmission Line

The Salt River Project and a consortium of other utilities proposed to construct a 412 km +/-500 kV transmission line between Boulder City, Nevada and Phoenix, Arizona. The line was granted certification by the Arizona Corporation Commission in 1985, without major opposition based on need, environmental, or health concerns. Because of lowered forecasted demand for power, work on this transmission line was postponed for many years, but is now under construction as a 500 kV ac transmission line capable of being converted to dc operation at some time in the future.

Implications

No utility has attempted to site any HVDC transmission lines since the late 1980's. Since that time, interest in potential health effects of air ions has completely diminished, no recent studies have raised health concerns. In theory, some of the controversies concerning the projects mentioned above possibly might not occur . However, the above examples serve to illustrate that in a persisting climate of general public concern and opposition to ac transmission lines and facilities, the siting of HVDC transmission lines may not be easier than a comparable ac transmission line, despite lesser environmental impacts. Experience has demonstrated that the acceptability of transmission lines is strongly influenced by public perception of, and reaction to, many aspects of the siting and certification processes. If these processes do not develop optimally, then public concern about potential health impacts of the transmission line electrical environment may be substantially heightened. One of the aspects that may foster public concern is the apparent novelty of the technology.

The implications of the above analysis for future deployment of HVDC transmission lines are: 1) the applicant should give considerable attention to the siting process and communication with the public; and 2) even more efforts need to be made to respond to anticipated public concern about potential health impacts than for an ac transmission line. This latter need is based upon the public reaction to the unfamiliarity of the technology. While there have been no adverse health impacts linked to HVDC transmission, the very novelty of the technology requires greater efforts to address and communicate credible scientific and health information to those raised questions about HVDC transmission lines.

10. ELECTRICAL ENVIRONMENTAL EFFECTS

10.1 INTRODUCTION

This chapter presents a survey of electrical environmental effects of overhead HVDC lines, with the exception of effects on human health which are addressed in earlier chapters. The text presents a discussion of corona and field effects in general for HVDC lines, especially as they compare to ac lines. These effects include radio and audible noise, and voltages and currents induced on objects in proximity to the line.

10.1.1 Corona and Field Effects

A fundamental physical fact is that the effects of voltage and current on an electrical conductor are not confined to the conductor itself, but are spread out throughout the surrounding space. For example, a conductor located above the earth may have a voltage of 100,000 volts with respect to the earth. This gives rise to a "space potential," a voltage distribution throughout the surrounding space. A bird starting from earth at zero volts would have a steadily increasing voltage until the bird lands on the conductor and attains 100,000 volts. The absolute magnitude of the space potential is itself of little general concern, because the important variable is the amount this space potential changes over small distances. For the 100,000 volt conductor, the space potential may change 3,000 volts in the first meter from the earth, but change 10,000 volts in the last centimeter to the conductor. The negative of the gradient (change) of the space potential is called the electric field.

Electric and magnetic fields are produced by both natural and man-made sources. The earth produces both a static electric and magnetic field that are comparable to fields from HVDC transmission lines. The earth's ambient electric field is usually directed downward with a magnitude of the order of 100 volts/meter. The direction and magnitude of the field vary with local conditions, such as during thunderstorms, when the electric field is usually (but not always) directed upward and can exceed 5,000 volts/meter (5 kV/m). The earth's magnetic field does not fluctuate as much with local conditions (although magnetic storms occur occasionally causing variations in the earth's magnetic field), but the magnitude of the field varies over the earth's surface, from a high of 600 to 700 milligauss in northern latitudes to a low of approximately 230 milligauss off the coast of Brazil.

HVDC lines also produce static (or constant) electric and magnetic fields. These electric and magnetic fields are truly static fields; that is, not varying with time in the same sense as fields from ac power transmission lines or radio antennas. The electric field from a dc line is properly denoted an electrostatic field, and the magnetic field from a dc line is properly denoted a magneto static field. The terms electric field and magnetic field cover the entire frequency spectrum from dc to light. The stress on proper terminology follows from earlier practice in the electric power industry to incorrectly call electric fields from ac lines electrostatic fields.

The electrostatic (dc) field is a function of the voltage on the transmission line, and the magneto static (dc) field is a function of the current on the transmission line. At typical power frequencies (e.g. 60 Hz), the electric and magnetic fields may be assumed to be quasi static. While truly time-varying, the period of the sinusoidal wave is sufficiently slow that static formulas can be used to calculate the fields with the one change that the voltages and currents are expressed as complex numbers (phasors). At frequencies used for power line carrier (50 to 350 kHz) through frequencies used for radio and television (500 kHz to beyond 1000 MHZ), the quasi static approximation no longer holds, and a coupled solution of Maxwell's equations for electric and magnetic fields must be sought.

The electric field near the surface of power line conductors, whether dc or ac, is of particular significance. As the conductor surface electric field increases, the electrical stress on the air causes ionization of the air molecules, a partial electrical discharge. This discharge is called corona, and is responsible for power loss, audible noise, and radio and television interference. For HVDC lines air ions produced by conductor corona migrate into the surrounding space. Ion migration is responsible for charge accumulation on objects near the HVDC line (insulated from earth).

Corona is a fundamental consideration in the design of both dc and ac lines. It affects size, bundling, spacing, and geometry of conductors. It determines an upper limit on the voltage which can be placed on any particular conductor array.

10.1.2 DC and AC Comparison

It is incorrect to directly apply 60 Hz environmental performance conclusions to dc, or 0 Hz. The environmental aspects of dc transmission lines may be summarized as follows:

- No 60 Hz magnetic fields
- Static (dc) magnetic fields
- No 60 Hz electric fields
- Static (dc) electric fields
- Air ions
- Audible noise
- Radio interference
- Television interference

Electrical environmental impacts of overhead power lines are conveniently divided under the headings of corona effects and field effects. Corona effects of both dc and ac lines include corona loss, and audible and radio noise. In addition, corona from HVDC lines produces air ions at locations away from the line conductors. These air ions are responsible for voltage build-up on insulated objects in close proximity to HVDC lines. Air ions exist, but are not a concern, for ac lines because the alternating electric field traps the corona-produced ions in the air space near the conductors.

Field effects primarily involve induction of voltage and current to objects near a power transmission line through capacitive or inductive coupling. Since a dc line operates at 0 Hz, there are no 60 Hz electric or magnetic fields, but there are dc (static) electric and magnetic fields. The electric field of an ac line couples voltages and currents to nearby objects through the capacitive network formed by the transmission line, nearby conducting objects, and ground. AC line electric field coupling is significant for vehicles and similar sized objects. The magnetic field of an ac line couples voltages and currents to parallel objects through the inductive network formed by parallel conductors. Magnetic field coupling is most significant for objects which parallel the transmission line for a considerable distance, such as telephone lines, pipe lines, and railroads. Both capacitive and inductive coupling are time-varying phenomena, that is they require a source which varies with time, or ac. Thus, capacitive and inductive coupling are not factors for normal operation of a HVDC line, although coupling during fault transients or line switching may be of interest during the time when current is changing.

DC magnetic fields can result in deflection of compass needles near the line. While this is generally of little significance, it should be considered in special cases, such as when a dc line crosses a navigation channel. DC magnetic fields can also affect the operation of video display terminals, especially when high-current dc circuits such as for railroad power supply are close to computer installations.

To illustrate the different corona and field effects and their relative magnitudes, it is fitting to give an example based on a comparison of an HVDC line with an ac line of comparable power transfer capacity. The HVDC line design is based on +/- 400 kV lines presently in service in the United States. Normal operation is 1000 megawatts (MW). For comparison, a 500 kV 3-phase ac overhead line has a surge impedance loading of 971 MW. Surge impedance loading is the power flow where the reactive power generated by the line capacitance equals the reactive power absorbed by the line reactance. It is frequently used as a rule of thumb value in comparing ac lines of different voltage and design. It is typical of normal loading of a 500 kV line 300 miles long. This length is appropriate to use for a dc comparison because of the normally long length of dc installations. Parameters for the dc line are given in Table 10.1, and parameters for the ac line are given in Table 10.2.

The dc and ac lines given in Tables 10.1 and 10.2 were designed for different span lengths, as indicated by the relative heights of the conductors at the structures. The dc line, constructed in a more rural area, has longer spans and consequently higher structures. Both lines have similar clearance requirements at midspan. For the purpose of the example calculations, both are assumed to have the same minimum midspan ground clearance. To make a reasonable comparison, environmental values are calculated for this minimum clearance. Use of minimum clearance is appropriate for electric and magnetic fields, because most evaluations are based on maximum field levels, which occur at the lowest conductor height. Audible and radio noise are typically calculated based on an average conductor height over the span. Greater clearance moves the conductors farther away and results in lower noise levels. For a comparison of dc and ac lines, it is appropriate to use the same average conductor height, and to simplify the comparison for those who would like to duplicate it with their own computer programs, minimum clearance was used for all calculations.

All calculations presented in this chapter were made with the Bonneville Power Administration Corona and Field Effects program. This program is based on extensive measured data taken by the U. S. Department of Energy and others.

Table 10.1

+/- 400 KV HVDC OVERHEAD TRANSMISSION LINE		
Line Loading	Megawatts	Amperes
Normal Operation	1000	1250
Continuous Overload	1100	1375
Maximum Current	1456	1820
Pole Spacing (2 Symmetrically Placed Poles)	12.2 m (40 feet)	
Pole Conductor: 2-Bundle 1590 kcmil Lapwing 45/7 ACSR	3.82 cm (1.504 inches)	
Bundle Spacing	0.46 m (18 inches)	
Pole Conductor Height at Structure	34.2 m (112 feet)	
Pole Conductor Minimum Ground Clearance at Mid-Span	10.7 m (35 feet)	
Shield Wire Spacing (2 Symmetrically Placed Shield Wires)	8.8 m (28.9 feet)	
Shield Wire Conductor: ½ Inch EHS Steel	1.27 cm (0.5 inch)	
Shield Wire Height at Structure	44.9 m (147 feet)	

Table 10.2

500 KV 3-PHASE AC OVERHEAD TRANSMISSION LINE		
Line Loading	Megawatts	Amperes
Surge Impedance Loading	971	1121
Loading for Comparison with HVDC Line	1000	1155
Horizontal (Flat) Phase Configuration Symmetrical About Center Line		
Phase Spacing	8.69 m (28.5 feet)	
Phase Conductor: 3-Bundle 954 kcmil Rail 45/7 ACSR	2.96 cm (1.165 inches)	
Bundle Spacing	0.46 m (18 inches)	
Phase Conductor Height at Structure	15.55 m (51 feet)	
Phase Conductor Minimum Ground Clearance at Mid-Span	10.7 m (35 feet)	
Shield Wire Spacing (2 Symmetrically Placed Shield Wires)	13.8 m (45.25 feet)	
Shield Wire Conductor: 7/16 Inch EHS Steel	1.11 cm (0.438 inch)	
Shield Wire Height at Structure	26.1 m (85.5 feet)	

10.2 CORONA EFFECTS

Corona and its related effects, such as audible noise and radio noise, occur whenever the electric field on the conductor surface exceeds the breakdown strength of the air. Audible noise is greatest for ac transmission lines during heavy rain or wet conductor conditions. With dc lines, radio and audible noise generally decrease during wet weather when the air ion activity around the conductor is greatly increased. This intense air ion activity surrounds the conductor with space charge which reduces the electric field at the surface of the conductor, thereby suppressing the intensity of the corona pulses. The audible noise from a dc line sounds more like a popping as opposed to a hissing or crackling for an ac line. The noise for a dc line is continuous, but at a much lower level than the noise level for a comparable ac line.

Radio and audible noise levels change with time. It is possible to develop a complete statistical distribution of these levels by long term measurements on a single line. For many purposes, it is customary to describe noise in terms of exceedence levels. Exceedence levels are stated in terms of L_N, where N is the percentage of time the noise exceeds the given value. For example, if radio noise is given as 45 dB L_{50} fair weather, it means that the noise is 45 dB above one microvolt/meter 50% of the time during fair weather. L_{50} and L_5 foul weather noise levels are frequently evaluated. The all-weather statistical distribution is in three general portions corresponding to fair weather, foul weather, and a transitional region. Normally L_{50} and L_5 foul weather statistics include both the foul weather and transitional portions of the overall distribution.

10.2.1 Radio and Television Noise

The positive polarity conductor is the primary source of dc transmission line audible noise and radio interference, with the noise produced by the negative pole about one half that from the positive pole. DC radio interference levels are decreased by rain, wet snow, and other atmospheric conditions which thoroughly wet the conductor. However, radio interference may increase slightly during the initial wetting period, and during dry snow. Wind also affects dc radio interference levels. The radio interference levels are increased by wind, with the greatest influence being when the direction of air flow is from the negative to the positive pole.

By comparison, radio noise from overhead ac power lines is produced by two distinct phenomena, corona and sparking. Corona occurs when the electric field at the conductor surface exceeds a critical value. This value is a function of conductor diameter, conductor surface condition, and atmospheric conditions. Corona can also occur on insulators and hardware. Conductor corona noise usually dominates over noise from insulators and hardware, unless glass insulators are used, or the line is in an unusually contaminated location. Glass insulators tend to be noisier than porcelain or polymer. Conductor corona noise drops off rapidly with increasing radio frequency, and is primarily of concern in the AM broadcast band (0.535 to 1.605 MHZ).

Sparking occurs at poorly conducting electrical connections. An example of such a connection is between individual units in a porcelain suspension insulator string which supports a jumper connection with little mechanical load on the insulators. Because of the small supported weight, a film of corrosion can form on the insulator pin. The capacitive voltage distribution across the insulators can cause sparking across the insulating film created by the corrosion. Other locations where sparking occurs are between tie wires and insulators on distribution lines, and on wood poles where staples make poor contact with ground down leads. Sparking is also called gap discharge. Because of the small size of the sparks, they are frequently referred to as microsparks, and the resulting noise as microsparking noise.

Sparking on both transmission and distribution lines can be a serious source of radio and television interference. The minimization of spark discharge noise is more of a maintenance matter than a design consideration. Experience indicates that for a line properly designed with respect to conductor corona, 90-95% of all listener/viewer noise complaints are sparking-related, and can be located and eliminated. Spark noise can extend into the ultra high frequency range (above 300 MHZ), and is the primary cause of television interference.

Evaluation of radio noise performance of any transmission line requires the consideration of three areas:

- Criteria
- Prediction
- Evaluation

It is insufficient to merely calculate a radio noise profile for a proposed line design with one of the available computer programs. Criteria to determine noise levels which cause annoyance are also necessary.

Some countries, such as Canada, have national standards for radio noise from overhead power lines. Others, such as the United States, have no overall standards, but rely on considerations of local land use and weather to determine the background noise level in a given location. The following steps are usually taken in the development of radio noise criteria for a specific transmission line:

1) Ascertain the radio station signal strength which exists at the edge of the right-of-way under different weather conditions. This may be done in several ways: by measurement of signal strengths at the line location; by estimation from radio station coverage maps which are usually given on their advertising rate schedule; or by application of FCC rules for signal strength to cover a specific type of terrain. FCC rules specify minimum signal strengths in millivolts per meter (mV/m) for different coverage areas. Radio station signal strength can also be given in decibels (dB) above 1 microvolt per meter. Expression of the signal strength in dB is particularly useful for assessing radio noise from electric power facilities. Signal strength levels taken from the FCC are given in Table 10.3.

Table 10.3

GROUNDWAVE FIELD STRENGTH REQUIRED FOR MINIMUM AM RADIO STATION COVERAGE		
Area	mV/m	dB
City Business or Factory Areas	10 to 50	80 to 94
City Residential Areas	2 to 10	66 to 80
Rural - All Areas During Winter or Northern Areas During Summer	0.1 to 0.5	40 to 54
Rural - Southern Areas During Summer	0.25 to 1.0	48 to 60

2) Determine the signal-to-noise ratio necessary for edge of right-of-way reception under the specific weather conditions. Results of listener tests of AM radio for corona noise produced by ac lines are given in Table 10.4.

Table 10.4

RECEPTION QUALITY FOR AM RADIO DETERMINED BY LISTENER TESTS	
Signal-to-Noise Ratio in dB	Reception Quality
>32	Entirely satisfactory
27-32	Very good, background unobtrusive
22-27	Fairly satisfactory, background plainly evident
16-22	Background very evident, speech easily understood
6-16	Speech understandable with severe concentration
<7	Speech unintelligible

Subjective evaluations of radio noise produced from dc lines indicate that dc line noise has a lower "nuisance value" than that from ac lines. A signal-to-noise ratio of 20 dB from a dc line is equivalent to a signal-to-noise ratio of somewhere between 23.5 to 28 dB for ac line noise.

3) Subtract the signal-to-noise ratio in dB from the radio station signal strength in dB above 1 microvolt/meter to give the allowable edge of right-of-way radio noise under the specific weather conditions.

4) Compare the developed criteria with the predicted edge of right-of-way radio noise from the line. If the noise is above the criteria, repeat the process, with a revised line design and possible reconsideration of the criteria.

Television interference can be evaluated in the same manner. Care must be taken in evaluating television noise to ensure that proper bandwidth corrections are made to relate the measuring receiver, computer program, and signal-to-noise ratio viewer reactions. These are frequently given on the basis of different bandwidths for television, and seemingly disparate numbers can often be traced to different bandwidths used for evaluation. Available data indicates that television interference is of little concern at distances beyond 25 meters from the center of the right-of-way.

DC power transmission lines can affect television reception by a mechanism other than corona or spark discharge. A television antenna located in the electric field of a dc transmission line may pick up ionic currents with consequent interference. If this interference occurs, it can be reduced by shielding the tips of the television antenna.

Figures 10.1-10.4 present the following calculated 1 MHZ radio noise lateral profiles for the example dc and ac transmission lines. 1 MHz is chosen because it is in the middle of the AM broadcast band and much previous literature presents 1 MHZ data.

10.1 DC line bipolar operation in fair weather and rain
10.2 DC line monopolar and bipolar operation
10.3 Comparison of dc and ac lines in fair weather
10.4 Comparison of dc line in fair weather and ac line in rain

Several observations may be gained from these figures:

- As previously discussed, radio noise from a dc power transmission line is higher in fair weather than it is during rain.

- Radio noise under all weather conditions is higher for bipolar operation of the dc line than it is for monopolar operation.

- For this particular comparison of dc and ac lines of comparable transmission capacity, the fair weather dc line noise is greater than the fair weather ac line noise, especially on the positive pole side of the line where the dc line noise is approximately 5 dB above the ac line noise for the same distance from the center of the line. However, because dc line noise has a lower signal-to-noise nuisance effect than ac line noise by 3.5 to 8 dB, both lines will have similar impacts on AM radio reception at the same distance from the line.

- Radio noise during rain increases for the ac line and decreases for the dc line.

- A comparison of the dc fair weather profile with the ac rain profile indicates the dc line is 13 to 15 dB quieter than the ac line under typical conditions which give higher noise profiles for each line type. The effect on a listener is even greater because of the relative nuisance effect of each type of noise.

It should be noted that the previous discussion is based on radiated conductor corona radio noise, which is the noise most likely to affect residents in proximity to a power transmission line in the U.S.A. Technical practices in some countries, and specific instances in the U.S.A. where lines are installed in areas with significant contamination deposition on insulators, may result in significant insulator radio noise. Partial discharge insulator noise is approximately the same for dc and ac insulators where the ac root-mean-square (rms) voltage equals the steady dc voltage. Conclusions of the relative performance of dc and ac lines deduced from Figures 10.1-10.4 should be unchanged by the additional consideration of insulator noise.

For an engineering evaluation of a dc line, it may be necessary to consider other influences of radio noise. For example, power line carrier (PLC) is frequently used for utility communication purposes. PLC is a system where frequencies between 20 and 490 kHz are superimposed on the power transmission line for relaying or voice communication channels. Carrier signals may also be employed on wire telephone circuits, both open wire and cable. HVDC converter stations produce noise in the carrier frequency range which must be considered in the design of power line carrier facilities and coordination with nearby open wire carrier installations.

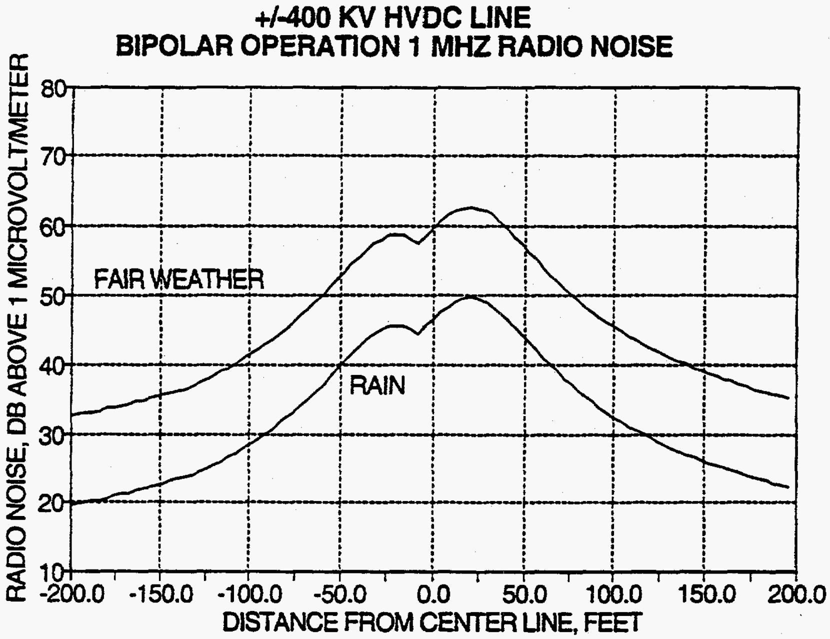

Figure 10.1 RN DC Line Bipolar Operation in Fair Weather

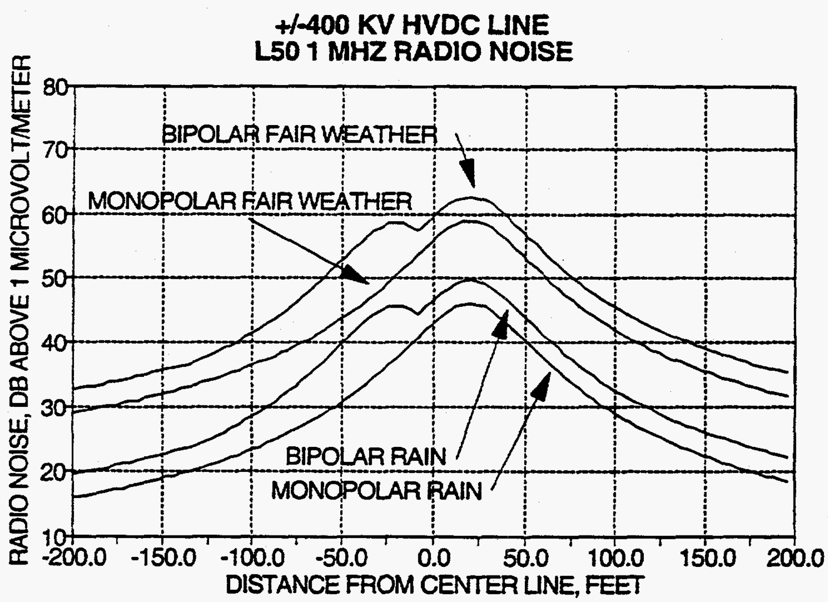

Figure 10.2 RN DC Line Monopolar and Bipolar Operation