Exhibit No. 111
Issues: HVDC Technology & Construction;
RTOs & Interconnection; Electric & Magnetic Fields
Witness: Anthony Wayne Galli
Type: Direct Testimony
Sponsoring Party: Grain Belt Express
Clean Line LLC
Case No.: EA-2014-0207
Date: March 26, 2014

MISSOURI PUBLIC SERVICE COMMISSION

CASE NO. EA-2014-0207

DIRECT TESTIMONY OF

DR. ANTHONY WAYNE GALLI, P.E.

ON BEHALF OF

GRAIN BELT EXPRESS CLEAN LINE LLC

March 26, 2014

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I. QUALIFICATIONS

Q. Please state your name, present position, and business address.

A. My name is Anthony Wayne Galli. I am Executive Vice President – Transmission and Technical Services of Clean Line Energy Partners LLC ("Clean Line"). Clean Line is the ultimate parent company of Grain Belt Express Clean Line LLC ("Grain Belt Express" or "Company"), the Applicant in this proceeding. My business address is 1001 McKinney Street, Suite 700, Houston, Texas 77002.

Q. What are your duties and responsibilities as Executive Vice President – Transmission and Technical Services of Clean Line?

A. I oversee and am responsible for the planning, engineering, design, construction, and other technical activities of Clean Line and its subsidiaries with respect to their transmission projects. I am also involved in developing strategy for Clean Line.

Q. What is the purpose of your testimony in this docket?

A. The purpose of my testimony is to (i) provide an overview of the physical and operating characteristics of the Grain Belt Express Clean Line transmission project ("Grain Belt Express Project" or "Project"), (ii) describe interactions with regional transmission organizations ("RTOs") Southwest Power Pool, Inc. ("SPP"), Midcontinent Independent System Operator, Inc. ("MISO"), and PJM Interconnection, LLC ("PJM"), (iii) discuss details relating to construction activities, including the anticipated construction schedule and potential vendor contracts, and (iv) address the issue of electric and magnetic fields ("EMF") associated with the Project.

Q. Please describe your education and professional background.

A. I received Bachelor of Science and Master of Science degrees from Louisiana Tech University and a Doctor of Philosophy degree from Purdue University, all in electrical engineering. I am a Senior Member of the Institute of Electrical and Electronics Engineers ("IEEE"), a member of the International Council on Large Electric Systems ("CIGRE"), and a registered Professional Engineer in the Commonwealth of Virginia.

I have over 15 years of experience in the electric transmission industry, in both technical and managerial roles, ranging from power system planning and operations to regulatory matters and project development. Just prior to my current position, I served as Director of Transmission Development for NextEra Energy Resources ("NextEra"), a subsidiary of NextEra Energy, Inc. (formerly FPL Group, Inc.), where I developed transmission projects under the Competitive Renewable Energy Zones ("CREZ") initiative in Texas. In this position, I focused on, among other issues, the development of high voltage direct current ("HVDC") transmission solutions in the CREZ, and I led all efforts in routing, siting, and engineering transmission lines in the CREZ projects, which were awarded to Lonestar Transmission (NextEra's newly formed utility in the state of Texas). Prior to my time at NextEra, I spent six years at SPP, where I led the implementation of several components of the SPP market and grew the SPP Operations Engineering Group over fourfold to help ensure reliable operations of the SPP grid as it moved toward a market paradigm. As the Supervisor of Operations Engineering at SPP, my group was responsible for the real-time and short-term engineering support of SPP's RTO functions. These duties included activities primarily directed toward maintaining real-time system reliability through engineering support for the SPP Reliability

Coordinator and Market Operations, performing short-term tariff studies, operational planning activities (e.g., processing outage requests), and engineering analysis support of the SPP Energy Imbalance Services Market. Additionally, my group led the implementation of several facets of the SPP market system and performed acceptance testing of various software systems.

My background also includes system planning experience with Southern Company Services, a subsidiary of Southern Company, where I analyzed expansion plans for 500 kilovolt ("kV") transmission facilities, and commercial power systems experience with Siemens Westinghouse Technical Services. Additionally, I have held academic positions at the university level and have helped design shipboard power systems for the U.S. Department of Defense.

Q. Have you testified previously before any regulatory commissions?

A. Yes, I have provided testimony in proceedings before the Federal Energy Regulatory Commission ("FERC"), the Public Utility Commission of Texas, the Kansas Corporation Commission ("KCC"), the Oklahoma Corporation Commission, the Illinois Commerce Commission, the Indiana Utility Regulatory Commission ("IURC"), and the Arkansas Public Service Commission.

II. OVERVIEW OF PROJECT

Q. Please provide a general description of the proposed Grain Belt Express Project and explain the RTOs to which it will interconnect.

A. The Grain Belt Express Project is an approximately 750-mile, overhead, $\pm$600 kV, multi-terminal HVDC transmission line ("HVDC Line") and associated facilities that will deliver wind-generated energy from western Kansas to utilities and customers in Missouri, Illinois, Indiana, and states farther east.. The wind energy will be independently developed within the geographic footprint of SPP and will be delivered to the geographic footprint of MISO and PJM via the Grain Belt Express Project. As such, the Project will be electrically interconnected to the SPP, MISO, and PJM systems. While the Project's electrical interconnections with both MISO and PJM will be designed to accommodate all or part of the wind energy being delivered by the Project, the electrical interconnection with SPP is primarily required to facilitate the alternating current ("AC") to direct current ("DC") conversion process and therefore will be designed to have a minimal power exchange with the SPP system during normal operations.

Q. Please describe the transmission facilities that Grain Belt Express proposes to build.

A. The Grain Belt Express Project will run from a tap of the new Spearville to Clark County 345 kV line in southwestern Kansas near Dodge City to an interconnection location in northeastern Missouri along Ameren Missouri's Maywood to Montgomery 345 kV transmission line and then on to American Electric Power's ("AEP") Sullivan 345 kV substation in Southwestern Indiana. This final point of interconnection provides direct access to the 765 kV network in PJM via two 345/765 kV transformers in AEP's Sullivan 765 kV substation. The Project will be capable of delivering up to 3,500 megawatts ("MW") of power to the PJM market and up to 500 MW of power to the MISO market through interconnections with the existing transmission grid in Indiana and Missouri, respectively.[1]

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[1] The power will be transmitted approximately 550 miles to near the Maywood 345 kV substation and then another approximately 200 miles east to the Sullivan substation. The Maywood converter station is expected to deliver up to 500 MW, pursuant to MISO interconnection studies, and will be rated at 1,000 MW in the event market demand later necessitates it. Grain Belt Express is currently studying the interconnection and delivery capability of 500 MW with MISO.

The HVDC portion of the Project will consist of the HVDC Line and three HVDC converter stations located near the substations described above. Each converter station will be capable of converting DC into AC or vice versa. The converter in Ralls County, Missouri will interconnect with the MISO system along a 345 kV AC transmission line connecting the Maywood substation and the Montgomery substation. The connection will be made via a single 345 kV circuit from the converter station to a nearby tap point along the transmission line connecting Maywood to the Montgomery 345 kV substation.

Q. Why has Clean Line decided to use HVDC technology for the Grain Belt Express Project?

A. HVDC is a more efficient technology for long haul transmission of large amounts of electric power because substantially more power can be transmitted with lower losses, narrower rights-of-way, shorter transmission towers and fewer conductors than with an equivalent high voltage AC ("HVAC") system. In general, when considering distance effects, long haul HVAC transmission lines require intermediate switching or substations approximately every 200 miles in order to segment the line to handle issues relating to voltage support, transient over-voltages, and transient recovery voltages. Additionally, HVAC lines used for long haul applications exhibit angular and voltage stability limitations, have a higher requirement of reactive power dependent upon loading, and have higher charging currents at light load.

In essence, it takes more lines (and thus more right-of-way) to move large amounts of power long distances with AC than it does with DC. The current school of thought is that at distances beyond approximately 300 miles, HVDC is the most efficient means to move more power. Yet HVDC and HVAC facilities can be quite complementary when considering the integration of large amounts of renewable power into the electric transmission grid.

The use of HVDC technology is the appropriate technology solution for the Grain Belt Express Project to move large amounts of power from variable generation sources (such as wind farms) over long distances, primarily or exclusively in one direction. In this context, DC lines result in a lower cost of transmission than AC lines. The use of HVDC technology has a number of distinct benefits, including the following:

(1) HVDC lines can transfer significantly more power with lower line losses over long distances than comparable AC lines.

(2) HVDC lines complement AC networks without contribution to short circuit current power or additional reactive power requirements.

(3) HVDC lines can dampen power oscillations in an AC grid through fast modulation of the AC-to-DC converter stations, and thus improve system stability.

(4) HVDC technology gives the operators complete control of energy flows, which makes HVDC particularly well-suited to managing the injection of variable wind generation.

(5) HVDC lines, unlike AC lines, will not become overloaded by unrelated outages, since the amount of power delivered is strictly limited by the DC converters at each end of the HVDC line, thereby reducing the likelihood that outages will propagate from one region to another.

(6) HVDC lines utilize narrower rights-of-way, shorter towers and fewer conductors than comparable AC lines, thereby making more efficient use of

transmission corridors, minimizing visual and land use impacts, and offering a transmission solution with a lower capital cost per mile.

Q. How is an HVDC converter station different than a typical AC substation?

A. In general, when referring to the transmission grid, substations function as junctures, where transmission and distribution lines meet and form a network. Within a typical AC substation, circuit breakers, switches, transformers (for changing voltage levels), protection and control equipment, capacitors, and perhaps line or shunt reactors can be found. When looking at an HVDC converter station, all of the aforementioned equipment would be easily recognized, as well. The primary difference is that an HVDC converter station contains two, side-by-side buildings called valve halls. The valve halls contain the power electronics that perform the conversion from AC to DC or from DC to AC. The HVDC converter station also includes a DC switchyard and many AC filter banks (capacitors and reactors, designed and connected to remove harmonics from the system). A typical HVDC converter station layout is provided in my **Schedule AWG-1**.

Q. What type of transmission structures will be utilized by the Project and how many?

A. In the design work that has been performed by POWER Engineers, Inc. ("POWER"), three primary structure types have been identified: traditional self-supporting lattice structures, tubular steel "monopole" structures, and self-supporting lattice mast structures, which have similar footprint dimensions as the tubular steel "monopole" structures. Other lattice structure types, such as guyed "vee" and guyed lattice mast structures, have also been identified in the preliminary engineering performed by POWER as being suitable structures. Grain Belt Express has not made a final determination as to the predominant structure type so that landowner preferences, project costs, local terrain, land use, and other relevant factors can be considered when making a final selection. It is likely that a mix of structures will be utilized to help maximize flexibility and minimize costs and impacts with respect to varying terrains and land uses.

The current designs for lattice towers and tubular steel monopoles allow for up to 1,500-foot spans for lattice towers and up to 1,200-foot spans for tubular steel monopoles or self-supporting lattice mast structures. Given conditions that allow for such spans, there would typically be four lattice structures per mile or five tubular steel monopoles or lattice masts per mile. However, the number of structures per mile may be higher in certain areas where shorter spans are necessary based on terrain and engineering constraints. On occasion, longer spans may be required. These longer spans typically are used for conditions such as river crossings and situations where sensitive areas such as wetlands must be avoided. Longer spans require larger structures than are needed for the typical 1,200-foot or 1,500-foot spans.

Q. Have you provided diagrams showing converter station configurations and structure types for the Project?

A. Yes, they are attached to my testimony as **Schedule AWG-2.**

III. RELIABLE INTERCONNECTION AND SAFE OPERATION OF THE GRAIN BELT EXPRESS PROJECT

Q. Will the Project provide a reliability benefit to the electric system in Missouri?

A. Yes. While the Grain Belt Express Project is not intended to prevent the bulk power system from falling below some predetermined, minimum level of reliability, the addition of a new transmission path that did not previously exist for additional energy resources to access consumer demand (load) will increase the transfer capability into the area and result in an increase in the reserve margin of the area where that demand is located. This will help further ensure that load within the area can be adequately served. Grain Belt Express witness Robert M. Zavadil of EnerNex, LLC explains in his testimony the measured reliability benefits in the form of a reduction to Missouri's loss of load expectation.

A. <u>NERC</u>

Q. Will the Project be designed in accordance with Good Utility Practice, applicable laws, and North American Electric Reliability Corporation ("NERC") criteria?

A. Yes. Grain Belt Express, along with its consultants, is actively engaged in various aspects of the Project design process. This includes studying the potential impacts of the Project during various system conditions and under various contingency scenarios in order to ensure that the systems to which the Project will interconnect will remain secure and compliant with NERC reliability standards. This is being accomplished through open stakeholder processes involving various RTOs and identified parties, potentially affected by the operation of the Project, via a series of system studies that I will describe in detail later in this testimony. NERC reliability standards became mandatory and enforceable (through the imposition of monetary penalties or other sanctions) in June 2007, pursuant to Section 215 of the Energy Policy Act of 2005 and subsequent regulations and orders of the FERC. Compliance with these standards is important to ensure the reliability of the bulk power system.

Q. How will Grain Belt Express comply with NERC's standards and protocols?

A. Grain Belt Express expects to be registered on the NERC Compliance Registry for the reliability functions of a "Transmission Owner," a "Transmission Operator," and a "Transmission Service Provider" (depending on the nature of its arrangements with a third party or parties to operate the Project, which could result in some or all of the Transmission Operator or Transmission Service Provider functions being assigned to the third party). Therefore, Grain Belt Express will be subject to applicable requirements of one or more NERC reliability standards in some or all of the following categories: Resource and Demand Balancing; Communications; Critical Infrastructure Protection; Emergency Preparedness and Operations Procedures; Facilities Design, Connections and Maintenance; Interchange Scheduling and Coordination; Interconnection Reliability Operations and Coordination; Modeling, Data, and Analysis; Personnel Performance, Training, and Qualifications; Protection and Control; Transmission Operations; Transmission Planning; and Voltage and Reactive.

Grain Belt Express will be prepared to comply with the requirements of the reliability standards that are applicable to its activities. Additionally, the Company is applying the results of studies that were conducted for the design of Clean Line's other projects to ensure that the Project will meet the National Electrical Safety Code (NESC) requirements and the tenets of Good Utility Practice.[2] Preliminary design criteria have been developed in order to guide this process, and are attached as Schedule **AWG-3**.

Q. Will Grain Belt Express comply with all relevant aspects of 4 CSR 240-23.010 (Electric Utility Reliability Monitoring and Reporting Submission Requirements), 4 CSR 240-23.020 (Electric Corporation Infrastructure Standards) and 4 CSR 240-

[2] FERC Order No. 888 defines "Good Utility Practice" as follows: "Any of the practices, methods and acts engaged in or approved by a significant portion of the electric utility industry during the relevant time period, or any of the practices, methods and acts which, in the exercise of reasonable judgment in light of the facts known at the time the decision was made, could have been expected to accomplish the desired result at a reasonable cost consistent with good business practices, reliability, safety and expedition. Good Utility Practice is not intended to be limited to the optimum practice, method, or act to the exclusion of all others, but rather to be acceptable practices, methods, or acts generally accepted in the region."

23.030 (Electrical Corporation Vegetation Management Standards and Reporting Requirements)?

A. Yes. Grain Belt Express is aware of the Commission's electric service reliability rules and will comply with all relevant aspects of 4 CSR 240-23.010 (Electric Utility Reliability Monitoring and Reporting Submission Requirements), 4 CSR 240-23.020 (Electric Corporation Infrastructure Standards) and 4 CSR 240-23.030 (Electrical Corporation Vegetation Management Standards and Reporting Requirements).

B. <u>SPP</u>

Q. What interaction has Grain Belt Express had with SPP, and what studies have been conducted as a result?

A. Grain Belt Express has worked with SPP to conduct bulk electric grid reliability studies with affected Transmission Owners and it will continue to do so. In collaboration with Siemens Power Technologies International ("Siemens PTI"), Grain Belt Express has met with affected Transmission Owners and has submitted various technical studies to SPP.[3] Siemens PTI conducted both steady state and dynamic stability studies, in accordance with SPP Criterion 3.5, simulating the effect of the Project to SPP's and other affected parties' electric systems. Criterion 3.5 requires entities requesting transmission interconnections to work with SPP and affected parties to ensure grid reliability. Parties were presented with the study models and reports in early 2013 and were given the opportunity to ask questions about the results and to request additional analyses.[4]

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[3] Meeting minutes and copies of the submitted studies can be viewed at http://www.grainbeltexpresscleanline.com/site/page/technical_studies. The Stability and Steady State Study Reports can be viewed at http://www.grainbeltexpresscleanline.com/site/page/technical_studies.

[4] The models used in SPP studies and the one-line diagram, attached as **Schedule AWG-5,** show the Project interconnecting directly to the Clark County substation. This is simply a modeling convenience

Furthermore, as part of Grain Belt Express' agreement with SPP, in the summer of 2013, SPP performed an independent review of the studies and provided their opinion prior to SPP Transmission Working Group approval. The final report from SPP's independent review is attached as Schedule **AWG-4**.

Q. Did Grain Belt Express work with SPP and affected parties to develop the scope of and to conduct studies under SPP Criterion 3.5?

A. Yes. Grain Belt Express initially met with SPP and affected parties on June 9, 2011 to develop the scope of the steady state and dynamic stability studies required under SPP Criterion 3.5. Based on the agreed-upon scope, the initial steady state results were shared with SPP and the affected parties on November 1, 2011 to gather their input and to incorporate any needed study scope modifications. Additional analyses were conducted based on feedback and the final steady state results were reviewed and vetted with SPP and affected parties during two webinars on February 1 and February 7, 2013. The final transient and dynamic stability study results have been completed and were also reviewed and vetted with SPP and the affected parties on February 13, 2013. As mentioned previously, the models used in these studies along with the study reports were made available to SPP and the affected parties when the study results were shared with them. In September 2013, the SPP Transmission Working Group passed a motion to "approve

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and, from a results perspective, is virtually identical to studying a tap of the Clark County – Spearville 345 kV line. The final report from SPP's independent review, attached as Schedule AWG-4, confirms that the results from the Project interconnecting directly to the Clark County substation or via a tap of the Clark County – Spearville 345 kV line is virtually identical.

the GBX [Grain Belt Express] studies completed to date as meeting their coordinated planning requirements under SPP Criteria ...."[5]

Q. What are the operational realities that will exist between Grain Belt Express and SPP with regard to the Project?

A. The Project is being designed so that during normal operating conditions, there is nominally zero active power exchange and very little, if any, reactive power exchange between the Grain Belt Express AC bus and the SPP grid. However, following the loss of a single-pole, some of the power transmitted by the Project will temporarily flow into the SPP grid. The results of the SPP Criterion 3.5 studies indicate that during this occurrence, using one of the future scenario cases, only one circuit in the SPP grid would be loaded above its applicable rating. For all other future scenarios included in the studies, the loss of a single pole does not cause any adverse impacts.

Q. What further steps need to be taken with SPP?

A. Following the Criterion 3.5 approval, Grain Belt Express is working with ITC Great Plains and Sunflower Electric Power Corporation on an interconnection service agreement which will include a requirement to conduct additional, detailed studies including a Facilities Study for the facilities needed to interconnect the Project to the SPP grid. Additionally, Grain Belt Express is continuing discussions with SPP staff regarding the need for appropriate operating agreements, seams agreements, and possible administrative requirements (e.g. tariff administration).

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[5] The motion can be found at: http://www.spp.org/publications/TWG%208.14-15.13%20Minutes%20&%20Attachments.pdf.

C. MISO

Q. What interaction has Clean Line had with MISO regarding the Grain Belt Express Project?

A. Initially, Grain Belt Express anticipated injecting 3,500 MW of power to the MISO market at the St. Francois 345 kV substation in eastern Missouri. However, after working with MISO, the interconnection studies showed that significant upgrades at and around the 345 kV St. Francois substation would be necessary for a 3,500 MW interconnection. The magnitude of the upgrades required, including several new transmission lines, made this initial proposal uneconomical. As a result, the Company examined alternatives that led to the current plan of injecting a smaller portion of the power into MISO in northeastern Missouri and transmitting the bulk of the power to PJM. MISO is currently studying the impacts of the Project delivering up to 500 MW of power into the existing 345 kV system in northeastern Missouri both at and near the Ameren Maywood 345 kV substation, pursuant to an interconnection request filed in September 2012 and subsequently assigned queue position J-255.

MISO completed a Feasibility Study for J-255 in October 2012, and the study is attached as **Schedule AWG-6**. The Feasibility Study did not identify any constraints associated with the 500 MW injection into MISO at the requested locations. Additionally, Grain Belt Express is working with PJM to complete the necessary studies for interconnection at the Sullivan 345 kV substation in Indiana. Currently, the J-255 queue position is in MISO's "parked" status in order to ensure that any applicable results from the PJM System Impact Study (which is expected to be completed during the second quarter of 2014) can be incorporated in the scope of the next level of analyses in MISO's interconnection process.

Q. What is the next level of analyses that MISO will perform as part of its interconnection process after completion of the Feasibility Study?

A. Following the conclusion of the Feasibility Study, MISO's interconnection process includes two additional levels of analysis: (i) System Planning and Analysis ("SPA") and (ii) Definitive Planning Phase ("DPP"). The SPA is an optional analysis that the interconnection customer may choose to bypass and proceed directly to the DPP. The scope for the SPA may include the following:

- Power flow
- Short circuit
- Steady state voltage
- Transient and voltage stability
- System protection
- Loss analysis
- Mitigation of constraints

The scope for the DPP involves MISO performing a System Impact Study and an Interconnection Facilities Study, which then is followed by a Network Upgrade Facility Study.

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D. PJM

Q. What interaction has Clean Line had with PJM regarding the Grain Belt Express Project?

A. In August 2011, Grain Belt Express submitted an interconnection request in PJM's merchant transmission queue and subsequently was assigned queue position X3-028. In January 2013, PJM completed a Feasibility Study[6] and subsequently initiated a System Impact Study in February 2013.

IV. FUNCTIONAL CONTROL

Q. What does a transfer of Functional Control entail?

A. The requirement to transfer Functional Control is to ensure that a transmission asset owner, Grain Belt Express in this case, cannot exercise undue discrimination in fulfilling its FERC Open Access Transmission Tariff commitments. FERC also ensures that undue discrimination cannot occur during the open season by requiring Grain Belt Express to file open season reports with FERC, which provide the terms of the open season; notice of open season; bid evaluation methodology; identity of parties purchasing capacity; and the amount, term, and price of the capacity.

Q. Will Grain Belt Express turn over Functional Control of the Project to a RTO or RTO-like entity?

A. Yes. Grain Belt Express could turn over Functional Control of the Grain Belt Express Project to SPP, MISO, or PJM.

[6] The PJM feasibility study can be viewed at the following location: http://www.grainbeltexpresscleanline.com/site/page/technical_studies.

Q. Has the Grain Belt Express determined which specific RTO or RTO-like entity will have functional control of the Project?

A. Yes. Grain Belt Express has made a decision to hand functional control of the Project to PJM. While all three of the RTOs that this Project will be interconnecting to are fully capable of taking over functional control of the Project, for operational and practical purposes, it was determined that PJM would be best positioned to have functional control since the majority of the energy transferred on the Project will be delivered to the PJM market. However, significant coordination will occur between Grain Belt Express, PJM, MISO, and SPP.

V. CONSTRUCTION ACTIVITIES

Q. What is the expected construction timeline of the Grain Belt Express Project?

A. I expect that construction could begin as early as 2016 and could take two to three years to complete. Lead times for delivery of HVDC converter stations are typically on the order of 36 months at the present time. The transmission line construction would need to be completed approximately six months prior to operation so that the converter stations can be fully tested. Construction could begin in several different areas of the Project simultaneously depending on labor availability and environmental conditions. The Project is expected to achieve commercial operation as early as 2018.

Q. Has Grain Belt Express secured the services of a third party firm to assist with the design and construction of the Project?

A. Yes. Grain Belt Express has secured the services of POWER Engineers, Inc. ("POWER") to serve the role of consulting engineer. POWER is an experienced engineering consulting firm founded in 1976 that has been providing advice and assistance in both the design and constructability analysis of the Project. Focusing primarily on the electric power industry, the firm has performed work in all parts of the country including Kansas, Missouri, and Illinois. The individuals we work with at POWER have significant experience in engineering and construction of transmission facilities. POWER has also performed preliminary engineering to specify design criteria and develop preliminary structure types and requirements for the Project, as described in **Schedule AWG-3.**

Q. Does the Company have agreements with any suppliers?

A. Yes. The Company has supplier agreements with ABB Inc. ("ABB"), Hubbell Power Systems, Inc. ("Hubbell"), and General Cable Industries, Inc. ("General Cable") that will support manufacturing jobs in factories in St. Louis, Centralia, and Sedalia. The Memorandum of Understanding ("MOU") with ABB designates it as the "Preferred Supplier" of AC transformers associated with the Project's AC collector system, which will connect new wind farms in Kansas with the HVDC Line. ABB will also make its engineering resources available to aid in the design of the transformers, which will be manufactured at ABB's St Louis manufacturing facility, supporting roughly 20 jobs.

The MOU with Hubbell designates it as the Preferred Supplier of conductor hardware and polymer insulators for the Project. Hubbell will manufacture the insulator cores and conductor hardware at its Centralia, Missouri facility, creating an estimated 52 jobs in Centralia over two to three years. Hubbell will also make its engineering resources available to aid in the design of conductor hardware assemblies and polymer insulators and work to establish a supplier base within the Project area states, including Illinois and Indiana to source raw material from businesses in states that host the Project.

The Grain Belt Express MOU with General Cable designates it as a Preferred Supplier of conductor for the Project. General Cable will manufacture roughly 23 million feet of steel core for the transmission line conductor and manage inventory and logistics in Sedalia, where it employs roughly 185 people, supporting roughly 10 Missouri jobs. General Cable has also committed to sourcing all of the aluminum rod used in the conductor they provide for the Project from the Noranda Aluminum smelter near New Madrid. These partnerships demonstrate Grain Belt Express' commitment to working with qualified, local businesses to maximize the economic benefits of the Project to Missouri.

Q. What is the estimated cost to construct the Project and the Missouri portion, specifically?

A. The total cost to construct the Project is expected to be approximately $2.2 billion, which includes the cost for the HVDC Line and the three converter stations. From this $2.2 billion, approximately $500 million is expected to be specifically associated with the Missouri portion of the Project, where roughly $400 will be for the transmission line and $100 million will be for the converter station in Missouri.

VI. ELECTRIC AND MAGNETIC FIELDS

Q. What are electric and magnetic fields?

A. In the context of the Project, electric and magnetic fields ("EMF") collectively refer to the static electric and magnetic fields produced by the HVDC transmission line. These fields are of a different nature (i.e., they are static) than the EMF produced by typical AC transmission lines, which are time-varying in nature.

Q. How is EMF measured?

A. Electric fields are measured in units of kilovolts per meter ("kV/m"). The International System of Units ("SI") measures magnetic fields with the SI-derived unit of Tesla ("T"), which is widely applied in Europe; however, in North America magnetic fields are most commonly reported in units of gauss ("G"). As an example, a typical refrigerator magnet produces a magnetic field around 0.005 T (5 millitesla ["mT"]) which translates to 50 G (50,000 milligauss ["mG"]).

Q. Is EMF something people encounter every day?

A. Yes. Electric charges and the fields associated with them are found everywhere. We routinely encounter static electricity from rubbing our feet across the carpet on a dry winter day, from brushing our hair when the humidity is low, or from weather conditions, such as storms, snow, and blowing dust. The friction from walking across the carpet can create a static electric field at the surface of the body as high as 500 kV/m. This static charge is easily dissipated by touching another surface (such as a doorknob) and transferring the charge. Electric fields are easily blocked by most objects such as walls, trees, and fences. Few man-made devices produce static electric fields as frequently as does nature, but standing near a DC electrified railway, or sitting in front of a computer screen or television with a cathode ray tube ("CRT") are examples. In the case of sitting in front of a CRT television or computer screen, one may be exposed to a static electric field of about 10 – 20 kV/m at a distance of approximately one foot.

Likewise, magnetic fields are very commonplace. The primary natural source of static magnetic fields is the earth itself; its geomagnetic field covers the entire earth. Man-made sources include permanent magnets (e.g., the magnets contained in a set of headphones), battery-powered appliances, magnetic resonance imaging ("MRI") scanners, and, as stated above regarding static electric fields, DC electric railways. The earth's magnetic field ranges from 300 mG at the equator to 700 mG at the magnetic north and south poles. An MRI machine produces magnetic fields between 15,000,000 - 40,000,000 mG. Battery powered appliances may produce magnetic fields between 3,000 – 10,000 mG.

Q. What are the expected electric field levels associated with the Project's operation?

A. Based on applicable EMF calculations from similarly rated HVDC lines, the highest electric field level calculated on the right-of-way is expected to be approximately 40 kV/m. This includes the contribution of both the nominal field (i.e., the field that is derived from the voltage on the conductor) as well as the charges on air molecules ("air ions"). The contribution of air ions to the electric field is affected by weather conditions and the number presented above is expected to be a worst case condition with the likelihood that lower values would be typical.

Q. How does the Project's EMF compare to typical EMF exposure in day-to-day life?

A. As noted above, for electric fields, one can easily experience exposure up to 500 kV/m just by walking across a carpeted floor on a dry winter day, which is more than ten times the highest value expected from the Project's operation. As also noted previously, the magnetic field exposure experienced on a daily basis or in the course of one's life can range from strengths that are similar to what would be experienced within the right-of-way of the Grain Belt Express Project to levels that are orders of magnitude higher.

Q. Are you aware of any recommended limits of exposure or other documented scientific literature regarding DC EMF?

A. Yes. While questions have been raised about the possibility that static fields affect health, these questions have focused on sources of extremely strong magnetic fields. Since the weak magnetic fields produced by DC transmission lines are similar to naturally occurring magnetic fields, those sources have not prompted similar questions. The following organizations have reviewed and summarized the research on exposure to static or slowly varying fields:

- International Agency for Research on Cancer ("IARC") in 2002.[7]
- Nation Radiological Protection Board of Great Britain in 2004.[8]
- World Health Organization ("WHO") in 2006.[9]
- International Committee on Electromagnetic Safety ("ICES") in 2002 and 2007.[10]
- The Advisory Group on Non-ionising Radiation for the Health Protection Agency of Great Britain (2008).[11]
- International Commission on Non-ionizing Radiation Protection ("ICNIRP") in 2009.[12]

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[7] International Agency for Research on Cancer, IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Vol. 80: Static and Extremely Low-Frequency (ELF) Electric and Magnetic Fields (Lyon, France, IARC Press, 2002).

[8] National Radiological Protection Board (NRPB), Advice on Limiting Exposure to Electromagnetic Fields (0-300 GHz), Vol. 15, No. 2 (Didcot, UK, 2004).

[9] World Health Organization, Environmental Health Criteria Monograph No. 232. Static Fields (Geneva, Switzerland, World Health Organization, 2006).

[10] International Committee on Electromagnetic Safety, IEEE Standard for Safety Levels with Respect to Human Exposure to Electromagnetic Fields 0 to 3 kHz C95.6-2002 (Piscataway, NJ, IEEE, 2002) (Reaffirmed 2007).

[11] Advisory Group on Non-ionising Radiation, Static Magnetic Fields, RCE-6, Documents of the Health Protection Agency (Chilton, UK, 2008).

[12] International Commission on Non-ionizing Radiation Protection, Guidelines on Limits of Exposure to Static Magnetic Fields, Health Physics, 96:504-514 (2009).

None of these panels found that the body of research indicates that strong static magnetic fields cause long-term health effects. The ICNIRP and the ICES have developed exposure limits both for the general public and for occupational workers to protect against known, acute effects that occur only at levels above those found in certain specialized medical, research, and industrial environments. The ICNIRP has established these limits at 4,000,000 mG and 20,000,000 mG for the general public and occupational workers, respectively. The ICES has established limits of 1,180,000 mG and 3,530,000 mG for the general public and for occupational workers, respectively for frequencies up to 0.153 Hz.

Q. How does the Project's magnetic field compare to the limits of exposure described above?

A. The maximum expected magnetic field of the Grain Belt Express Project would be similar to that of the earth (~500 mG) and more than a thousand times lower than the aforementioned exposure limits (~4,000,000 mG).

Q. What is a Global Positioning System?

A. A Global Positioning System ("GPS"), is a space-based navigation system that depends on a series of geosynchronous satellites to provide time and location signals to receivers on earth.

Q. What is corona?

A. In the context of transmission lines, corona refers to a partial discharge of energy that ionizes air molecules resulting mostly in heat, as well as audible and electromagnetic noise. Corona occurs along the surface of conductors on high voltage transmission lines where irregularities (e.g., nicks on the conductor or debris such as dead mosquitoes) occur. If the electric field becomes sufficiently concentrated at these irregularities, the insulating properties of air break down, producing corona.

Q. Does corona create radio noise?

A. Yes. The radio noise produced by corona, if strong enough, can create interference with signal reception in a certain band of frequencies in the electromagnetic spectrum. The radio frequency portion of electromagnetic spectrum is typically defined from 3 kilohertz ("kHz") to 300 gigahertz ("GHz"). Corona primarily produces radio noise in the range of 0.1 megahertz ("MHz") to 10 MHz, with the power of radio noise decreasing rapidly with frequency; that is, the radiated power at 10 MHz is significantly lower than at 0.1 MHz. The highest levels of radio noise are measured underneath the transmission line and diminish with distance away from the conductors. Some devices that operate in the lower frequency ranges of the corona discharge are potentially susceptible to interference. Such devices as amplitude-modulated ("AM") radio station receivers operating in the 0.52 – 1.72 MHz range could be noticeably affected when close to a transmission line, e.g., the static you hear on your AM radio when you drive under the conductors of a high-voltage transmission line.

Frequency-modulated ("FM") radio stations operate in the range between 88 – 108 MHz and are not typically affected by radio noise from transmission lines. Real Time Kinematic ("RTK") systems, which are ground-based controls used to make differential calculations and improve positional accuracy of GPS, receive GPS satellite signals at 1227.60 MHz and 1575.42 MHz frequencies. RTK systems transmit and receive terrestrial signals typically at Ultra High Frequencies ("UHF"), which are greater than 300 MHz. Since both GPS and terrestrial signals on which RTK systems rely are at far higher frequency than the upper range of frequencies of significant corona noise, the terrestrial and the satellite signals are very unlikely to be affected by the corona noise.

Q. Will the Grain Belt Express Project interfere with GPS signals?

A. It is extremely unlikely. As I have pointed out, frequencies that are used to communicate between orbiting satellites and GPS units, including those associated with farm equipment, are much higher than the frequencies of radio noise from transmission lines. Therefore, GPS units will operate with their traditional degree of accuracy near and under high voltage transmission lines. Reports published by consultants to Manitoba Hydro (the provincial agency that operates two large HVDC projects similar to the Grain Belt Project) concluded:

> The differences between the ground truth positions established using conventional survey and the GPS observations indicate that transmission lines that supply Direct Current have no appreciable effect on either GPS measurements or ultra high frequency radios/cell phones that supply GPS correction messages. The results obtained were well within the manufacturers quoted equipment accuracies (i.e., centimeter level).[13]

A similar conclusion regarding these DC transmission lines was reached by engineers in the Position, Location and Navigation Group at the University of Calgary: [14]

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[13] Pollock & Wright, "Effects of Transmission Lines on Global Positioning Systems" (2011) at p. 10. See PLAN Group, "Manitoba Hydro DC-Line GNSS Survey Report" (Nov. 2011); http://www.hydro.mb.ca/projects/bipoleIII/eis/BPIII_GPS_Reports_November%202011.pdf

[14] J.B. Bancroft, A. Morrison, G. Lachapelle, "Validation of GNSS under 500,000 V Direct Current (DC) Transmission Lines," Computers and Electronics in Agriculture, 83:58, 66 (2012).

> GNSS [Global Navigation Satellite Systems] data collected under two 500 kV HVDC bipole lines were analyzed .... No transmission line effect on GNSS measurements was found to affect the quality of the navigation solutions. In addition, the test results showed normal operation of a commercially available survey grade RTK system and its radio link (450 MHz) for static and perpendicular test segments perpendicular to the transmission lines.

Q. What kinds of structures could disrupt GPS signals?

A. GPS signals can be physically blocked by objects such as dense forest canopy or they can be degraded by reflections off large solid objects like commercial buildings or agricultural structures like barns or silos. It is theoretically possible that the signal from a single GPS satellite could be blocked or degraded by a transmission structure.

Q. Could this result in a loss of functionality for a GPS system operating near a transmission line?

A. It is extremely unlikely that this could result in a loss of functionality for a GPS receiver in an agriculture setting. The United States Government ensures that at any given time there are at least 24 functioning GPS satellites in geosynchronous orbit in all parts of the sky and many GPS receivers today make use of other sources of satellite signals as well. A GPS receiver requires a signal from only three satellites to calculate the horizontal position on earth. All GPS receivers regularly add and drop satellites, and receive a signal from 12 or more satellites simultaneously. Hence, it is unlikely that a brief or even prolonged blockage of a single satellite would adversely affect GPS operation.

Q. When major transmission projects are undertaken, concerns regarding EMFs are sometimes raised. Does Grain Belt Express believe EMFs present a health threat to people, plants, or animals?

A. No. There is no conclusive evidence to support the contention that EMFs from transmission lines are linked to health related risks to humans, plants or animals. This conclusion is based primarily on the 2006 report produced by the Oak Ridge National Laboratory attached as **Schedule AWG-7**. Furthermore, the IARC, the WHO, the ICES and the ICNIRP (cited above) have all concluded that the current body of research does not indicate that strong static electric or magnetic fields cause long-term health effects. Clean Line has also retained Exponent, an expert consultant in the area of EMF health risks, to prepare a brochure for use in our public outreach and communication efforts. The brochure explains the nature of EMFs created by DC transmission lines, summarizes the scientific study of their effects, and provides references to documents produced by the scientific community. A copy of the brochure is attached as **Schedule AWG-8**.

Q. Does this conclude your testimony?

A. Yes, it does.

BEFORE THE PUBLIC SERVICE COMMISSION
OF THE STATE OF MISSOURI

In the Matter of the Application of Grain Belt Express Clean Line LLC for a Certificate of Convenience and Necessity Authorizing it to Construct, Own, Control, Manage, Operate and Maintain a High Voltage, Direct Current Transmission Line and an Associated Converter Station Providing an Interconnection on the Maywood 345 kV Transmission Line	)	Case No. EA-2014-0207

AFFIDAVIT OF ANTHONY WAYNE GALLI

STATE OF Texas)
) ss
COUNTY OF Harris)

Anthony Wayne Galli, being first duly sworn on his oath, states:

1. My name is Anthony Wayne Galli. I am Executive Vice President – Transmission and Technical Services of Clean Line Energy Partners LLC .

2. Attached hereto and made a part hereof for all purposes is my Direct Testimony on behalf of Grain Belt Express Clean Line LLC consisting of 27 pages, having been prepared in written form for introduction into evidence in the above-captioned docket.

3. I have knowledge of the matters set forth therein. I hereby swear and affirm that my answers contained in the attached testimony to the questions therein propounded, including any attachments thereto, are true and accurate to the best of my knowledge, information and belief.

[signature]
Anthony Wayne Galli

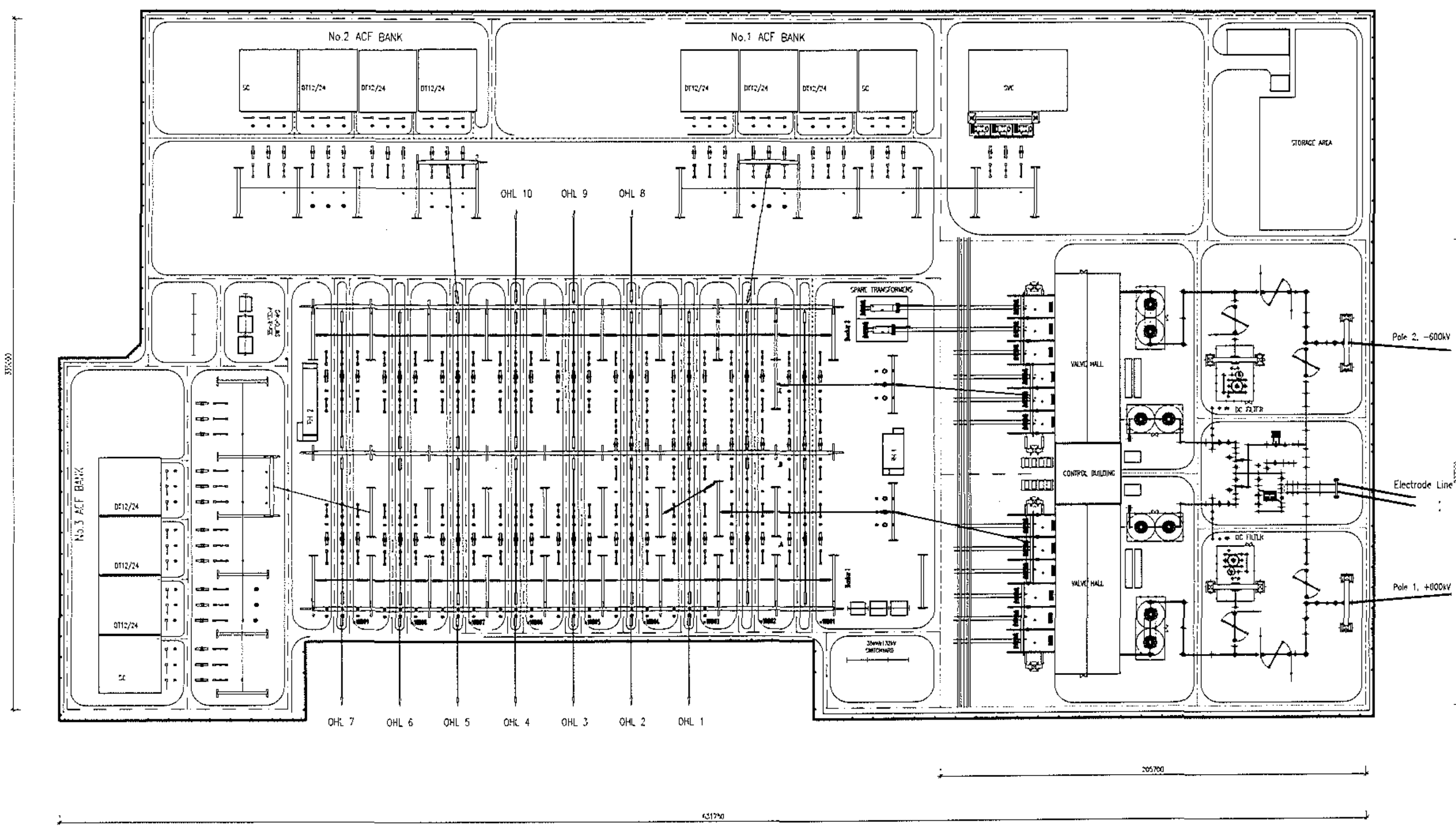
Subscribed and sworn before me this 25 day of March, 2014.

[signature]
Notary Public

My commission expires: 7-22-2015

JUDY BLANKENSHIP
Notary Public, State of Texas
My Commission Expires
July 22, 2015

81996296\V-1



Schedule AWG-1 - Page 1 of 1

1:1000	
CLEAN LINE HVDC CONVERTERS	
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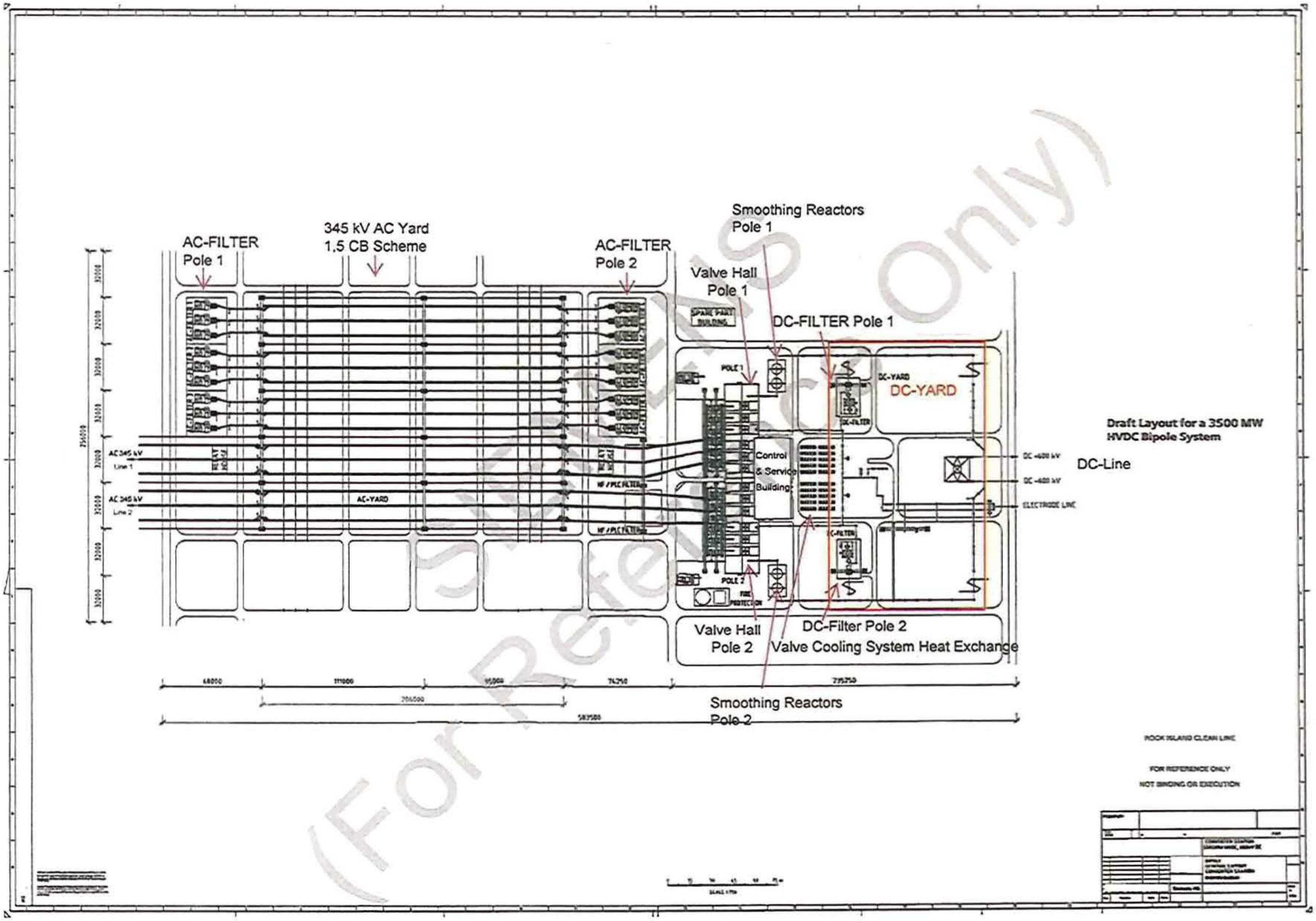
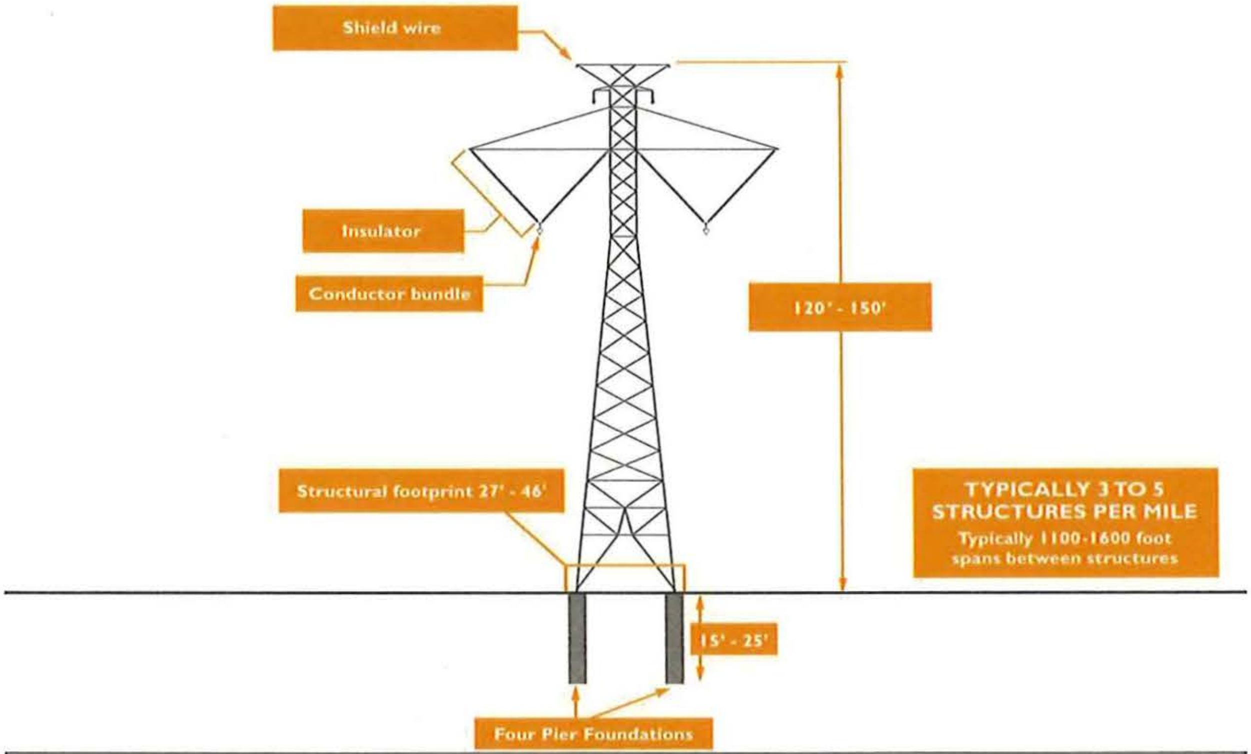
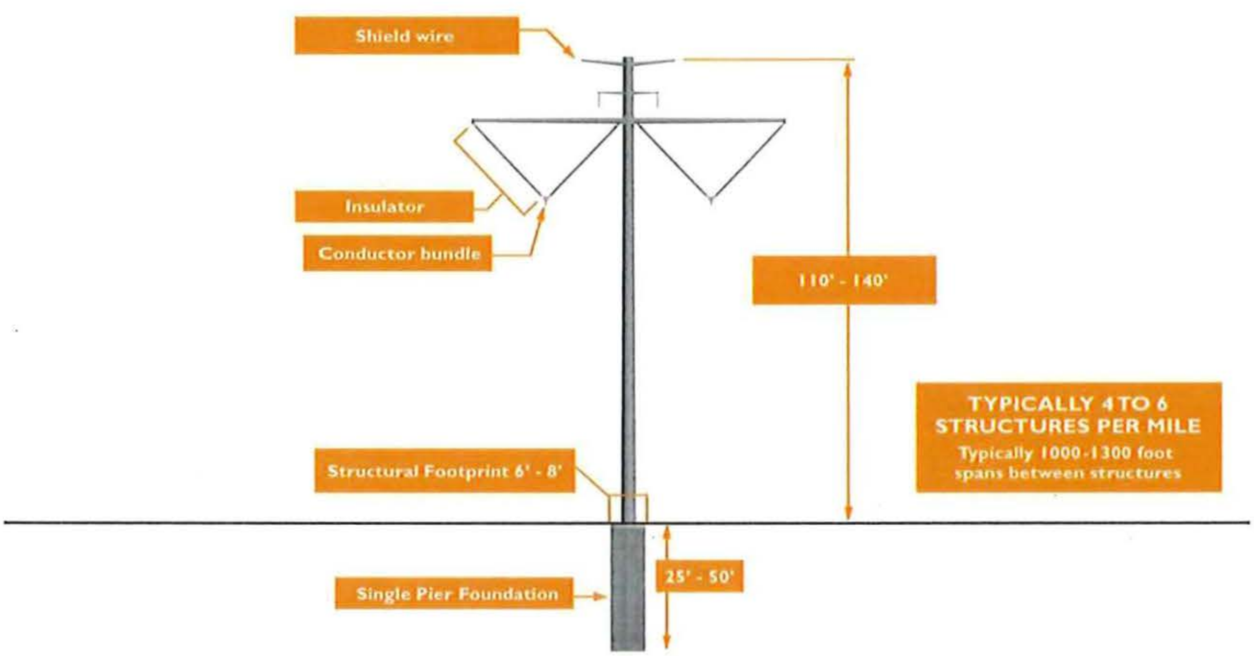
Siemens AG	(1) E50105 - R2851 - V025 - 0


AC-FILTER
Pole 1
345 kV AC Yard
1,5 CB Scheme
AC-FILTER
Pole 2
Smoothing Reactors
Pole 1
Valve Hall
Pole 1
DC-FILTER Pole 1
DC-YARD
Control
& Service
Building
DC-Line
Valve Hall
Pole 2
DC-Filter Pole 2
Valve Cooling System Heat Exchange
Smoothing Reactors
Pole 2
AC-YARD
Draft Layout for a 3500 MW
HVDC Bipole System
ROCK ISLAND CLEAN LINE
FOR REFERENCE ONLY
NOT BINDING OR EXECUTION

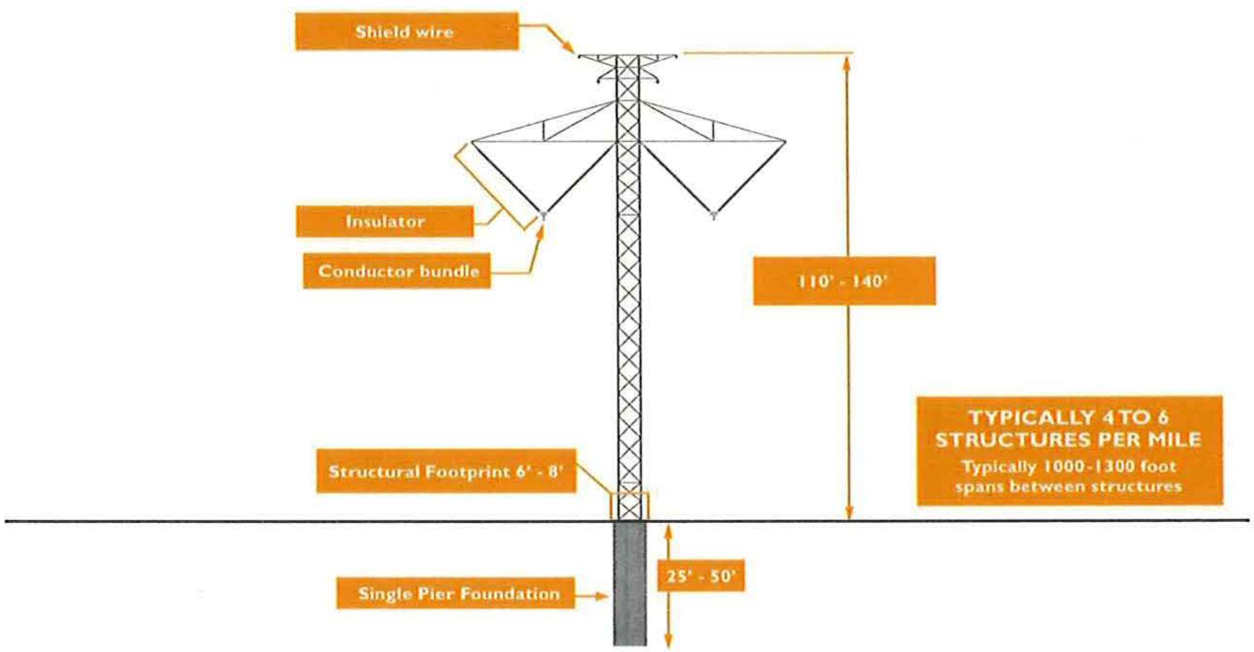
TYPICAL LATTICE STRUCTURE: 120 - 150 FEET



TYPICAL MONOPOLE STRUCTURE: 110 - 140 FEET



TYPICAL LATTICE MAST STRUCTURE: 110 - 140 FEET



January 27, 2011

CLEAN LINE ENERGY

GRAIN BELT EXPRESS HVDC LINE
PRELIMINARY DESIGN CRITERIA

PROJECT NUMBER:
121586

PROJECT CONTACT:
BRIAN BERKEBILE
EMAIL:
BRIAN.BERKEBILE@POWERENG.COM
PHONE:
803-835-5902

POWER ENGINEERS

PRELIMINARY DESIGN CRITERIA

PREPARED FOR: CLEAN LINE ENERGY
PREPARED BY: BRIAN BERKEBILE
PHONE 803-835-5902
EMAIL BRIAN.BERKEBILE@POWERENG.COM

REVISION HISTORY		
DATE	**REVISED BY**	**REVISION**
A	BHB	DRAFT for Review

TABLE OF CONTENTS

ABBREVIATIONS

ACSR:	Aluminum Conductor, Steel Reinforced
ACSS:	Aluminum Conductor, Steel Supported
ACCR:	Aluminum Conductor Composite Reinforced
ADSS:	All Dielectric Self-Supporting Fiber Optic Cable
AFL:	America Fujikura Ltd.
AGS:	Armor Grip Support
ASCE:	American Society of Civil Engineers
FC:	Sag Tension Limit, Final After Creep Condition
FL:	Sag Tension Limit, Final After Load Condition
Hz:	Hertz
I:	Sag Tension Limit, Initial Condition
kcmil:	1000 Circular Mills
kips:	1000 pounds
kV:	kilovolts
Manual No. 74	ASCE Manual and Report on Engineering Practice No. 74 "Guidelines for Electrical Transmission Line Structural Loading
N/A	Not Applicable
NESC:	National Electrical Safety Code, 2007
OHSW:	Overhead Shield Wire
OPGW:	Fiber Optic Ground Wire
ROW:	Right-of-Way
RUS:	Rural Utilities Service
TBD:	To Be Determined
TW:	Trapezoidal Shaped Conductor

GENERAL

Project Information

Owner's Name:	Clean Line Energy Partners ("Clean Line")
Project Name:	Grain Belt Express HVDC transmission line
Length:	Approximately 500 miles
Voltage:	+/- 600 kV DC (Bi-Pole)
Planned Energization Date:	Approximately 2015 or 2016

Correspondence/Project Personnel

POWER Engineers, Inc.

Project Manager		Brian Berkebile
	Email:	Brian.berkebile@powereng.com
	Phone:	803-835-5902
	Fax:	803-835- 5999
	Address:	POWER Engineers, Inc.
		1057 521 Corporate Center Drive Suite 150
		Fort Mill, South Carolina 29707
Project Management Support		Shayne Wright
	Email:	swright@powereng.com
	Phone:	281-765-5505
	Fax:	281-765-5599
	Address:	POWER Engineers, Inc.
		509 N Sam Houston Pkwy East Suite 200
		Houston, Texas 77060
Project Engineer T-Line Design		Tim Kautz
	Email:	tkautz@powereng.com
	Phone:	803-835-5901
	Fax:	803-835- 5999
	Address:	POWER Engineers, Inc.
		1057 521 Corporate Center Drive Suite 150
		Fort Mill, South Carolina 29707

Project Engineer		Brian Furumasu
Electrical Studies	Email:	Brian.furumasu@powereng.com
	Phone:	503-293-7124
	Fax:	503-293-7199
	Address:	POWER Engineers, Inc.
		9320 SW Barbur Boulevard Suite 200
		Portland, OR 97219
Project Consultant		Dave Wedell
	Email:	dwedell@powereng.com
	Phone:	314-851-4024
	Fax:	314-8514099
	Address:	POWER Engineers, Inc.
		12755 Olive Blvd, Suite 100
		St. Louis, MO 63141

Client

Project Manager		Wayne Galli, Ph.D., P.E.
		Vice President, Transmission and Technical Services
	Email:	wgalli@cleanlineenergy.com
	Phone:	(832) 319-6337
	Fax:	(832) 310-6311
	Address:	Clean Line Energy Partners, LLC
		1001 McKinney, Suite 700
		Houston, TX 77002

Project Description

This project involves developing a Preliminary Design and Budgetary Cost Estimate for Clean Line Energy Partner's ("Clean Line") proposed Grain Belt Express HVDC transmission line. This project is currently in the conceptual stage. The purpose of the Preliminary Design is to advance the project definition from the current conceptual level to a preliminary design level, which will serve as the basis for developing budgetary cost estimates for the transmission line. These estimates will, in turn, be used by Clean Line in their on-going project economic analyses.

Clean Line has stated that the desired operating voltage for the project is +/- 600 kV. However, they are also interested in having a ball-park estimate for the project if constructed for an operating voltage of +/- 500 kV. Therefore, while the preliminary design will be performed assuming +/- 600 kV, enough data and analysis will be performed at the appropriate tasks to allow development of the desired estimate for a +/- 500 kV project.

This preliminary design work requires creation of an initial design criterion, selection of several representative conductor configurations, conceptual design of several potential families of line structures, development of a conceptual PLS_CADD line model for the preferred line corridor, general engineering/technical support for line routing activities (by Others), field reconnaissance of potential line routes, and preparation of budgetary cost estimates for line construction. The basis for the criteria and selections included in our work plan will largely be POWER's experience in this area with reference to appropriate existing projects, and will be supplemented by analysis when appropriate.

Is desired by Clean Line, POWER can provide the value-added tasks described in Task 7 of POWER's Work Plan. These services will allow Clean Line to refine its conceptual design and better understand the cost and design limits of each corridor or route it analyzes. The value added tasks include:

- Identify Potential Locations for Ground Electrodes

CODE(S) AND LOADING CONDITIONS

Controlling Code(s)

NESC:	NESC Heavy District NESC Extreme Wind, adjusted for 100-year return period NESC Extreme Ice with Concurrent Wind, adjusted for 100-year return period
Location or State Specific:	TBD in final design, if appropriate
Client Specific:	TBD

Loading Conditions For Non-Deadend Structures

Case	Description	Weather Case	Ref	Cable Condition	Vert. Load Factor	Wind Load Factor	Tension Load Factor	Strength Reduction Factor
1	NESC HEAVY ALL WIRES INTACT (STEEL & CONCRETE)	0°F, 0.5" ICE, 4 PSF	NESC 253-1 / 261-1A	Initial	1.5	2.5	1.65	1
2	EXTREME WIND ALL WIRES INTACT (STEEL & CONCRETE)	60°F 97 MPH (100 YR RP) ASSUME 200' STR WITH 500' SPAN 24.3 PSF ON WIRE 26.3 PSF ON STR	NESC 253-1 / 261-1A	Initial	1.0	1.0	1.0	1
3	NESC EXTREME ICE WITH CONCURRENT WIND ALL WIRES INTACT (STEEL & CONCRETE)	15°F 1.25" ICE (100 YR) 4.1 PSF WIND	NESC 253-1 / 261-1A	Initial	1.0	1.0	1.0	1
4	F2 TORNADIC WIND ON STRUCTURE WITH NO WIRES	60°F, 157 MPH (63.1 PSF)	ASCE #74 2.7.1	Not Applicable	1.0	1.0	1.0	1
5	EVERYDAY LOADS	60°F		Initial	1.0	1.0	1.0	1
6	CONSTRUCTION, SNUB-OFF, 3:1	0°F		Initial	1.5	1.5	1.5	1
7	STRINGING/BROKEN SHIELD WIRE LOAD	0°F, 4 PSF		Initial	1.5	1.5	1.5	1
8	STRINGING/BROKEN CONDUCTOR LOAD	0°F, 4 PSF		Initial	1.5	1.5	1.5	1

Notes:

1. Load cases 1 through 4 shall be analyzed assuming a foundation rotation of 1.72° (3%) when used with pole structures.
2. Load case 2 is a maximum deflection case when used with pole structures. Deflection at the pole tip shall be limited to 9% of the above ground structure height under this load condition. The total of 9% includes 1.72° (3%) due to foundation rotation.
3. Load case 5 is for deflection control of pole structures under every day conditions. The maximum deflection for tangent structures is one pole tip diameter. The maximum deflection for angle structures at the pole tip is 1 ½ % of the above ground height. Angle structures not meeting this requirement shall be cambered.
4. For structure load calculations, the vertical span will be approximately 1.5 times the horizontal span unless actual span conditions are worse.
5. Load Case 2 shall be analyzed with the wind in a transverse direction, at a 45° yawed angle and with a longitudinal wind.
6. Load Case 6, snub-off, is applied with wires snubbed off at three horizontal to one vertical. For single circuit structures, all wires shall be snubbed off. For double circuit structures, all wires on one circuit and two shield wires shall be snubbed off.
7. Load Case 7, stringing shield wire, accounts for a stringing block getting hung up. The longitudinal load applied to the structure at any one shield wire position shall be equal to 100% of the tension in the shield wire. All other wire loads should be assumed intact.

8. Load Case 8, stringing conductor, accounts for a stringing block getting hung up. The insulator string is assumed to swing longitudinally at a 45° angle. The longitudinal load to be applied at any one conductor pole position shall be equal to the stringing tension x number of sub-conductors per pole x .6 residual tension factor x 1.1 overload factor. The other conductor pole and both shield wire locations should be assumed intact.
9. All load cases shall include the weight of the insulators and hardware plus 800 lb. additional vertical load at the tip of each arm to account for two maintenance men and equipment.
10. Load Case 4 shall be for wind on structure only with no wires attached. Structure shall be analyzed with the wind in a transverse direction, at a 45° yawed angle and with a longitudinal wind.
11. Insulators will be designed for the following overload factors and strength reduction factors (reference RUS Bulletin 1724E-200 Paragraph 8.9.1)
    a. Case 1: Overload Factor = 1.0, Strength Reduction Factor = 0.4
    b. Cases 2, 3: Overload Factor = 1.0, Strength Reduction Factor = 0.5 for non-ceramic, 0.65 for ceramic and glass
12. All lattice structural members shall be able to hold a 350 lb load, applied vertically at their midpoint, conventionally combined with the stresses derived from Load Case 5.

Loading Conditions For Deadend Structures

Case	Description	Weather Case	Ref	Cable Condition	Vert. Load Factor	Wind Load Factor	Tension Load Factor	Strength Reduction Factor
1	NESC HEAVY ALL WIRES INTACT (STEEL & CONCRETE)	0°F, 0.5" ICE, 4 PSF	NESC 253-1 / 261-1A	Initial	1.5	2.5	1.65	1
2	EXTREME WIND ALL WIRES INTACT (STEEL & CONCRETE)	60°F 97 MPH (100 YR RP) ASSUME 200' STR WITH 500' SPAN 24.3 PSF ON WIRE 26.3 PSF ON STR	NESC 253-1 / 261-1A	Initial	1.0	1.0	1.0	1
3	NESC EXTREME ICE WITH CONCURRENT WIND ALL WIRES INTACT (STEEL & CONCRETE)	15°F 1.25" ICE (100 YR) 4.1 PSF WIND	NESC 253-1 / 261-1A	Initial	1.0	1.0	1.0	1
4	F2 TORNADIC WIND ON STRUCTURE WITH NO WIRES	60°F, 157 MPH (63.1 PSF)	ASCE #74 2.7.1	Not Applicable	1.0	1.0	1.0	1
5	EVERYDAY LOADS	60°F		Initial	1.0	1.0	1.0	1
6	NESC HEAVY DEADEND ALL WIRES REMOVED FROM ONE SPAN (STEEL & CONCRETE)	0°F, 0.5" ICE, 4 PSF	NESC 253-1 / 261-1A	Initial	1.5	2.5	1.65	1
7	EXTREME WIND DEADEND ALL WIRES REMOVED FROM ONE SPAN (STEEL & CONCRETE)	60°F 97 MPH (100 YR RP) ASSUME 200' STR WITH 500' SPAN 24.3 PSF ON WIRE 26.3 PSF ON STR	NESC 253-1 / 261-1A	Initial	1.0	1.0	1.0	1
8	NESC EXTREME ICE WITH CONCURRENT WIND; DEADEND; ALL WIRES REMOVED FROM ONE SPAN; (STEEL & CONCRETE)	15°F 1.25" ICE (100 YR) 4.1 PSF WIND	NESC 253-1 / 261-1A	Initial	1.0	1.0	1.0	1

Notes:

1. Load cases 1 through 4 shall be analyzed assuming a foundation rotation of 1.72° (3%) when used with pole structures.
2. Load case 2 is a maximum deflection case when used with pole structures. Deflection at the pole tip shall be limited to 9% of the above ground structure height under this load condition. The total of 9% includes 1.72° (3%) due to foundation rotation.
3. Load case 5 is for deflection control of pole structures under every day conditions. The maximum deflection for tangent structures is one pole tip diameter. The maximum deflection for angle structures at the pole tip is 1 ½ % of the above ground height. Angle structures not meeting this requirement shall be cambered.
4. For structure load calculations, the vertical span will be approximately 1.5 times the horizontal span unless actual span conditions are worse.
5. Load Cases 6, 7, 8 shall be used to verify all deadend structures are designed to carry all wires deadended on one side of the structure.
6. Load Case 2 shall be analyzed with the wind in a transverse direction, at a 45° yawed angle and with a longitudinal wind.
7. All load cases shall include the weight of the insulators and hardware plus 800 lb. additional vertical load at the tip of each arm to account for two maintenance men and equipment.
8. Load Case 4 shall be for wind on structure only with no wires attached. Load Case 4 shall be analyzed with the wind in a transverse direction, at a 45° yawed angle and with a longitudinal wind.
9. Insulators will be designed for the following overload factors and strength reduction factors (reference RUS Bulletin 1724E-200 Paragraph 8.9.1):
    a. Case 1, 6: Overload Factor = 1.0, Strength Reduction Factor = 0.4
    b. Cases 2, 3, 7, 8: Overload Factor = 1.0, Strength Reduction Factor = 0.5 for non-ceramic, 0.65 for ceramic and glass.
10. All lattice structural members shall be able to hold a 350 lb load, applied vertically at their midpoint, conventionally combined with the stresses derived from Load Case 5.

WIRE

Transmission Conductor	
Size (kcmil/AWG):	2156 kCMIL
Composition (ACSR, AAC, etc.):	ACSR
Code Word:	Bluebird
Diameter:	1.762 inches
Weight:	2.511 lbs/ft
Rated Breaking Strength:	60,300 lbs
Design Voltage:	600 kV HVDC
Typical Operating Voltage:	600 kV HVDC
Maximum Operating Voltage:	632 KV HVDC
Maximum Conductor Temperature (Temperatures calculated using IEEE 738 methodology for predicted line loadings under normal and emergency conditions):	Normal Regime: 64 Deg C (148 Deg F) Emergency Regime: 71 Deg C (160 Deg F)

For additional information, see Appendix E-Sag & Tension File, Appendix F-Ampacity Calculations, and Appendix J-Preliminary Conductors Comparison.

OPGW
There will be two OPGW, one to protect each pole.

See Appendix B-OPGW Detailed Specification, Appendix C- Lightning Algorithm: Expected Charge Calculation at Line Location, and Appendix D-OPGW Outer Layer's Wire Diameter Calculation based on Expected Lightning Charge at Line Location.

Size (kcmil/AWG):	49AY85ACS-2C
Composition (EHS, AW, etc.):	12 Aluminum Clad Steel Wires ACS20.3% IACS 2 Aluminum Alloy Wires AY6201-T81 2 Stainless Steel Tubes 304 containing 6-24 fibers each and gel
Diameter:	0.591 inches
Weight:	0.473 lbs/ft
Rated Breaking Strength:	25,369 lbs
Number of Fibers:	12-48, depending on final project requirements

Shield Wire

Size (kcmil/AWG):	Not Applicable for this Project
Composition (EHS, AW, etc.):	Not Applicable for this Project
Diameter:	Not Applicable for this Project
Weight:	Not Applicable for this Project
Rated Breaking Strength:	Not Applicable for this Project

CONDUCTOR RATING CRITERIA

The following table summarizes conductor ampacity calculated using IEEE 738 methodology under normal and emergency loading conditions, using the following assumptions:

Ambient air temperature = 40 deg C (104 deg F), Wind Speed=2 ft/s, Emissivity factor = 0.5; and Solar absorptivity factor = 0.5.

See Appendix F-Ampacity Calculations, for other parameters used in these calculations, and the resulting maximum operating temperatures for the conductors analyzed.

Circuit	Conductor	Voltage (kV)	Normal Ratings				Emergency Ratings (20% over Normal Ratings)			
			Winter		Summer		Winter		Summer	
			MW	Amps	MW	Amps	MW	Amps	MW	Amps
Grain Belt Express	ACSR Bluebird 3 sub-conductors per pole	Nominal: 600 Maximum: 632	3720 At rectifier	3100 Per pole 1033.3 Per sub-conductor	3720 At rectifier	3100 Per pole 1033.3 Per sub-conductor	4464 At rectifier	3720 Per pole 1240 Per sub-conductor	4464 At rectifier	3720 Per pole 1240 Per sub-conductor

WIRE SAG/TENSION LIMITS

Conductor Sag-Tension Limits

The following table summarizes all sag-tension limits considered. The most stringent limit will be utilized to control the sag-tension in each span, or an agreed upon control tension will be used that will also meet the requirements below. See Appendix E-Sag & Tension Files.

Weather Case				Sag or Tension Limit		
Wind (psf)	Ice (inches)	Temp (°F)	Cond.	NESC Limit	Southwire Sag10 Program Limit	Project Specific Limit
4	1/2	0	I	60% RBS	50% RBS	50% RBS
24.3	0	60	I	--	--	75% RBS
4.1	1.25	15	I			75% RBS
0	0	60	I	35% RBS	--	--
0	0	60	F	25% RBS	--	-
0	0	0	I	--	33.3% RBS	33.3% RBS
0	0	0	F	--	25% RBS	25% RBS
0	0	-20	I	--	--	Uplift Condition
4	1/2	0	I	--	--	Slack Tension Into Substation D.E. Frame. 5000 lbs maximum per sub-conductor. Max per HVDC pole = 5000 lbs x no. of sub-conductors.
24.3	0	60	I	--	--	
4.1	1.25	15	I	--	--	

OPGW Sag-Tension Limits

The following table summarizes all sag-tension limits considered. The most stringent limit will be utilized to control the sag-tension in each span, or an agreed upon control tension will be used that will also meet the requirements below. See Appendix E-Sag & Tension Files.

Weather Case				Sag or Tension Limit		
Wind (psf)	Ice (inches)	Temp (°F)	Cond.	NESC Limit	Southwire Sag10 Program Limit	Project Specific Limit
4	1/2	0	I	60% RBS	50% RBS	50% RBS
24.3	0	60	I	--	--	60% RBS
4.1	1.25	15	I			60% RBS
0	0	60	I	35% RBS	--	--
0	0	60	F	25% RBS	--	<= 85% of the Conductor Sag at the Same Loading Condition
0	0	0	I	--	33.3% RBS	33.3% RBS
0	0	0	F	--	25% RBS	15% RBS
0	0	-20	I	--	--	Uplift Condition
4	1/2	0	I	--	--	Slack Tension Into Substation D.E. Frame. 3000 lbs maximum per OPGW
24.3	0	60	I	--	--	
4.1	1.25	15	I	--	--	

OPGW to Conductor Sag Ratios Requirements (to ensure shielding angles are maintained):

OPGW Sag @ 60 F, No Wind, No Ice, Final <= 85% Conductor Sag @ 60 F, No Wind, No Ice, Final

OPGW Sag @ 32 F, No Wind, **0.5" Ice**, Final <= 95% Conductor Sag @ 32 F, No Wind, No Ice, Final

Creep-Stretch Criteria

Condition for Final Sag after Load (Common Point):	NESC Heavy Rule 250 B: 0 Deg F, 4 PSF Wind, 0.5" Ice
Condition for Final Sag after Creep:	60 Deg F

Galloping

Double-loop galloping will be assumed for spans greater than 600 feet. Single-loop galloping will be assumed for spans less than 600 feet. Galloping ellipses will be allowed to overlap up to 10% of the elliptical major axis.

The weather case used to calculate swing angle used during galloping analyses will be 2 psf wind, 1/2" ice, 32°F final. The weather case used to calculate the ellipse size will be 0 psf wind, 1/2" ice, 32°F final.

Aluminum in Compression

It will be assumed that outer aluminum strands can go into compression under high temperature.
The maximum virtual compressive stress for ACSR Bluebird conductor will be assumed to be 1.5 ksi, and for ACCR/TW Pecos conductor (used in Mississippi River Crossing Span) will be assumed to be 1.25 ksi.

STRUCTURES

Circuits

No. Circuits (Single or Double):	2-Pole Horizontal HVDC with Earth Return (preferred) 2-Pole Horizontal HVDC with Dedicated Metallic Ground Returns (potential option to be reviewed)
Bundled:	3 conductors per bundle (pole)
Guyed or Self-Supporting:	Potential both guyed and self-supporting structures

Material

Wood (DF, WRC, preservative):	Do not consider wood
Steel (self-weathering, painted, galv.):	Potential weathering steel and galvanized steel
Concrete:	Potential concrete
Other:	

Configuration

Single Pole:	Potential single pole structure types: • Self-supporting Steel Tubular • Self-supporting Concrete
H-Frame	No
3-Pole:	No
Lattice:	Consider the following lattice tower types • Self-supporting Steel Lattice, • Guyed Single Mast or Vee

Other:	Consider the following additional structure types: • Cross Rope Suspension, Guyed Steel Lattice (with two foundations) • Cross Rope Suspension, Guyed Steel Lattice (Vee Configuration with a single foundation) • Guyed Single Mast or Vee Tubular Steel

Are Transposition Structures Required: YES ☐ NO ☑

Foundations

Type:	Drilled Pier
Geotechnical Data Available:	YES ☐ NO ☑
Geotechnical Study Required:	YES ☑ NO ☐ Desktop geotechnical study will be performed to determine soil types that may be encountered along the line and to classify them into several primary groups with typical soil design parameters to allow for estimated designs for budgetary purposes.
Design Criteria for Foundations subject to Lateral Loads	Drilled piers and direct embed poles subject to lateral loads will be designed per POWER standard as shown in Appendix K.
Design Criteria for Foundations subject to Uplift/Compression Loads	Drilled piers and direct embed poles subject to uplift/compression loads will be designed per POWER standard as shown in Appendix K.

Calculated Lightning Outages
Calculated outages from lightning will not exceed 1 outage per 100 miles per year per HVDC pole.

Distance Between Deadends
A deadend structure will be placed approximately every 5 miles.

Other

Shield Angle (If Required): Inside: Maximum 15 degrees Outside: Maximum 15 degrees

Raptor Protection: YES ☐ NO ☐ Distance: TBD

Maximum or Minimum Pole Height Limitations (specify): TBD

Annodes Required: YES ☐ NO ☐ TBD

GUYS AND ANCHORS

Guys

Guy Strand (size, material):	TBD
Guy to Pole Attachment:	
Pole Eye Plate:	TBD
Pole Band:	TBD
Guy Hook:	TBD
Other:	
Guy Connection	
Pole Attachment:	
Preformed:	TBD

3-Bolt: TBD
Automatic: TBD
Other:
@ Anchor:
Preformed: TBD
3-Bolt: TBD
Automatic: TBD
Other:

Guy Strain Insulators
Type: TBD

Guy Guards
Locations Required: TBD
Plastic: TBD Metal: TBD
Color: TBD Cattle Stub: TBD
Other (describe):

Anchors
Type:
Plate: N/A Size: N/A
Screw: TBD Size: TBD
Log: N/A Size: N/A
Concrete (describe): TBD
Other (describe): TBD
Rod: Length: TBD Diameter: TBD
Anodes Required: YES ☐ NO ☐ TBD

HARDWARE

Deadend Attachment

Description	Bolted	Compression	Other (describe)
Transmission Conductor [(1)]		X	
Shield Wire		N/A	
OPGW	X		Preformed

[(1)]Corona free hardware required: YES ☑ NO ☐

Suspension Attachment

Description	Formed Tie	Trunion Clamp	Suspension Clamp	Armor Rod	Line Guard	AGS	Other (Describe
Transmission Conductor [(1)]	N/A	N/A	TBD	TBD	N/A	TBD	
Shield Wire	N/A	N/A	N/A	N/A	N/A	N/A	N/A
OPGW	N/A	N/A	TBD	TBD	N/A	TBD	

[(1)]Corona free hardware required: YES ☑ NO ☐

Bracing
Transmission:

Wood: N/A Steel: TBD
Other (describe):

Vibration Analysis
For preliminary cost estimating, vibration analysis will be performed using Vibrec software. For final design, vibration analysis would be performed by the damper supplier.

Spacer Requirements
Spacer dampers will be utilized on conductors and will be installed such that:

- The spacer dampers will be spaced symmetrically in each span with a maximum spacing of 200 ft, or asymmetrically, with 10-15% detuning, with maximum spacing of 272 ft, per CIGRE rules.
- Number of spacer dampers that will be installed in jumper strings: three (if 2 jumper strings are used-rectangle cross arm) or two (if 1 jumper string is used-triangle cross arm); two spacer dampers will be used in the jumper loop. The spacer dampers will be equally spaced between the deadends.

INSULATION

Type-Transmission

I-String:	To Be Considered
V-String:	To Be Considered; Currently Preferred Configuration.
Horizontal Post:	N/A
Horizontal Vee:	N/A
Horizontal Jumper Post:	N/A
Vertical Jumper Post:	N/A

Material Transmission

Porcelain:	To Be Considered
Glass:	To Be Considered; Currently Preferred Material
Polymer:	To Be Considered
Other (fog, etc.):	To Be Considered
Corona Rings:	To Be Considered
End Fittings:	To Be Considered

Ratings-Transmission

					Electrical Characteristics *				
					DC Withstand Voltage*				
Structure Type	Impact Strength (in*lbs)	No. Bells/Sheds & Size	Insulator Weight (lbs) with hardware	Total Minimum Length (ft)	Dry one minute (kV)	Wet One minute (kV)	Dry lightning impulse withstand (kV)	Structure Type	Impact Strength (in*lbs)
Light Suspension Line Angle= 0-2 deg V-String Angles: 45 deg (L) 45 deg (R)	400 in.lbs	Single V-String: Each String: (41) 6-3/4"x13"	Each String: 1150 lbs Single V-String: 2x 1150= 2300 lbs	Each String: 23' (w/o hardware) 25' (with hardware)	150	65	140	225	1x50=50 kips
Basic Suspension Line Angle= 0-2 deg V-String Angles: 45 deg (L) 45 deg (R)	400 in.lbs	Single V-String: Each String: (37) 7-5/8"x 14-1/8"	Each String: 1450 lbs Single V-String: 2x 1450= 2900 lbs	Each String: 23' (w/o hardware) 25' (with hardware)	170	75	150	255	1x66=66 kips
Medium Suspension Line Angle= 0-2 deg V-String Angles: 45 deg (L) 45 deg (R)	400 in.lbs	Double V-String: Each String: (41) 6-3/4"x13"	Each String: 1150 lbs Double V-String: 4x 1150= 4600 lbs	Each String: 23' (w/o hardware) 25' (with hardware)	150	65	140	225	2x50=100 kips
					Electrical Characteristics *				
					DC Withstand Voltage*				
Structure Type	Impact Strength (in*lbs)	No. Bells/Sheds & Size	Insulator Weight (lbs) with hardware	Total Minimum Length (ft)	Dry one minute (kV)	Wet One minute (kV)	Dry lightning impulse withstand (kV)	Structure Type	Impact Strength (in*lbs)
Heavy Suspension Line Angle= 0-2 deg V-String Angles: 45 deg (L) 45 deg (R)	400 in.lbs	Double V-String: Each String: (37) 7-5/8"x 14-1/8"	Each String: 1450 lbs Double V-String: 4x 1450= 5800 lbs	Each String: 23' (w/o hardware) 25' (with hardware)	170	75	150	255	2x66=132 kips
River Crossing Heavy Suspension Line Angle= 0-2 deg V-String	400 in.lbs	Double V-String: Each String: (37) 7-5/8"x 14-1/8"	Each String: 1450 lbs Double V-String: 4x 1450= 5800 lbs	Each String: 23' (w/o hardware) 25' (with	170	75	150	255	2x66=132 kips

Angles: 45 deg (L) 45 deg (R)				hardware)					
Small Angle Suspension Line Angle= 2-10 deg V-String Angles: 20 deg (L) 35 deg (R)	400 in.lbs	Double V-String: Each String: (37) 7-5/8"x 14-1/8"	Each String: 1450 lbs Double V-String: 4x 1450= 5800 lbs	Each String: 23' (w/o hardware) 25' (with hardware)	170	75	150	255	2x66=132 kips
Medium Angle Suspension Line Angle= 10-30 deg V-String Angles: 12 deg (L) 65 deg (R)	400 in.lbs	Triple V-String: Each String: (41) 6-3/4"x13"	Each String: 1150 lbs Triple V-String: 6x 1150= 6900 lbs	Each String: 23' (w/o hardware) 25' (with hardware)	150	65	140	225	3x50=150 kips
Deadend Line Angle= 0-45 deg & Deadend Line Angle= 45-90 deg	400 in.lbs	Quadruple DE String: Each String: (50) 6-3/4"x13" 1 Jumper String: Single I-String (41) 6-3/4"x13"	Each String: 1455 lbs 1 Jumper: 1150 lbs Quadruple DE String: 4x 1455 =5820 lbs Both sides of structure: 2x 5820+ 1x1150= 12790 lbs	Dead end Insulator: 28' (w/o hardware) 33' (with hardware) Jumper: 23' (w/o hardware) 25' (with hardware)	150	65	140	225	4x50=200 kips (each side of structure) 2x200=400 kips (both sides of structure)

Data based on toughened glass, ball & socket coupling, Sediver's DC fog type: 50 kips (N220P/C-171DR) and 66 kips (F300PU/C-195DR).
*Electrical characteristics in accordance with IEC 61325.

RIGHT-OF-WAY

Description
Location of Line in ROW: Assumed center
ROW Width: Assumed 175' based on 1500' typical spans.

Right-of-Way Width Calculations for Blowout

Load Case 1: 0 PSF, No Ice, All Temperatures, Final (NESC 234 A.1)
Load Case 2: 6 PSF, No Ice, 60°F, Final (NESC 234 A.2)
Load Case 3: Extreme Wind 24.3 psf, No Ice, 60°F, Final

Minimum clearances to be maintained from the blown out conductor to the edge of right-of way shall be as follows. Load Cases 1 and 2 are based on maintaining NESC clearance to buildings. See NESC 234 B. Clearances for Load Case 3 are not governed by NESC. This case is a criteria designed to keep the

conductors on the right-of-way under an extreme wind. These clearances include a 3' buffer to accommodate survey and construction tolerances.
For clearances to the ROW, see also Appendix A- Clearances Calculation Tables.

	Clearance for ±600 kV nominal & ±632 kV maximum
Load Case 1	25 ft*
Load Case 2	22 ft*
Load Case 3	0 ft – May vary by location

*See Appendix A- Clearances Calculation Tables.

The maximum structure deflection, including foundation rotation, for single shaft steel structures will be assumed at 9% of structure above ground height for Load Case 3 and 5% for Load Case 2. For lattice towers the maximum structure deflection will be assumed at 1% of the structure above ground height.

Electric Field Affects

Electric field calculations will be prepared using the Corona and Field Affects Program (CAFEP) developed by the Bonneville Power Administration. The calculations will be based on a maximum line to line voltage of the nominal 600 kV plus 5% (or 632 kV) at the sending end. Typical approximate structure configurations will be used along with a sample of the possible conductor bundling scenarios. Calculated values will be compared to the limits listed below as a reference. Note that Kansas and Missouri do not have any published limits.

IEEE Standard C95.6-2002 Limits

- Maximum E-field at edge of right-of-way: 5 kV/m
- Maximum E-field on the right-of-way: 20 kV/m

Corona

POWER will prepare corona effects calculations using the CAFEP software and the same scenarios as the electric field calculations. Clean Line Energy will provide the audible noise (AN) and AM radio interference (RI) limits to be maintained at the edge of right-of-way. If no values are provided, the typical industry guidance of 40 dB μV/m will be used for RI and the EPA recommendation of no greater than 55 dBA will be used for AN. All values are calculated at the edge of the right-of-way.

In addition, the corona losses along the line will be calculated manually for the same scenarios as above. The calculations will assume a line length of 800 miles as the specific line length is yet to be determined.

CLEARANCES

All clearances will be determined using 600 kV DC, nominal, pole-to-ground, and 632 kV DC, maximum, pole-to-ground.
Also, for comparison purposes, clearances were calculated using an "AC equivalent" voltage (600 kV DC = 735 kV AC).
See Appendix A-Clearances Calculation Tables.

Voltage System

All systems are considered effectively grounded or systems where ground faults are cleared by promptly de-energizing the faulted section, both initially and following subsequent breaker operations. The maximum operating voltage is the normal voltage plus 5%.

Clearance to Structure/Insulator Swing

The maximum and minimum insulator swings will be limited by minimum clearances required to the structure. This clearance will be to the arm, tower body, or to the pole. The load cases considered for insulator swing as it relates to clearance to structure will be as follows:

Load Case 1:	0 PSF Wind, No Ice, All Temperatures, Final
Load Case 2:	6 PSF, No Ice, 60°F, Final (NESC 235 E.2)
Load Case 3:	Extreme Wind, No Ice, 60°F, Final

Minimum clearances to be maintained from the closest line conductor or other hot element to the face of the metal structures shall be as follows:

	Clearance for ±600 kV nominal & ±632 kV maximum
Load Case 1	17.33 ft
Load Case 2	17.33 ft
Load Case 3	5 ft

Load Case 1 required clearance based on air gap equivalent (dry arc distance) of tangent insulator. Load Case 2 clearance based on NESC Table 235-6. Load Case 1 and 2 minimum clearances increased to 17.33' to meet IEEE 516-2009 MAD (Minimum Approach Distance) for tools (12.33') and the Working Space (4.5').

Load Case 3 based on EPRI T/L Reference Book +/ -600 KV HVDC Lines where the mechanical case Extreme Wind corresponds to the electrical case Steady State , normal regime, Figure 10-3 page 145 and Fig.10-4, Page 146: 4.1', to which it was added a buffer of 0.9'.

See Appendix A-Clearances Calculation Tables.

Ground Clearance

NESC:	34' (w/3' buffer) (See Appendix A-Clearances Calculation Tables).
REA:	N/A
Other:	N/A

Water Clearance for River Crossing Spans

NESC:	55' (w/3' buffer) (See Appendix A- Water Clearances Calculation Tables).
REA:	N/A
Other:	N/A

The water clearance was determined based on NESC Rule 232D, Table 232-3, f (DC Calculation) and NESC Rule 232, Table 232-1, 7 (AC Equivalent Calculation). It might change, based future requirements from the Corps of Engineers, or other regulators.

5 milli Amp Rule

This rule, NESC Rule 232.C.1.c, does not apply to HVDC lines because a DC line will not create a steady-state current as occurs with AC lines.

Clearance Between Wires on Different Supporting Structures

NESC: Horizontal: 35 ft (w/3 ft buffer); Vertical: 28 ft(w/ 3 ft buffer) (Reference NESC Rule 233)

REA: N/A
Other: N/A

Clearance to Structures of Another Line
NESC: 22 ft (w/3 ft buffer) (Reference NESC Rule 234B)
REA: N/A
Other: N/A

Horizontal Clearance Between Line Conductors at Fixed Supports
CASE 1: The Horizontal clearance at the structure, of the same or different circuits, shall be per NESC 235B.3.a Alternate Clearance: Pole-to-Pole (horizontal configuration): 34.8' (w/3 ' buffer).

CASE 2: The Horizontal clearance at the supports, of the same or different circuits, shall also meet requirements according to sags per NESC 235B.1.b(2) :Pole-to-Pole (horizontal configuration): 27' (w/3' buffer).

CASE 3: Galloping

Refer to section titled "Galloping".

Vertical Clearance Between Line Conductors
Note: the poles (conductors) of the DC lines will be located horizontally, so these vertical clearances are just theoretical. Only the distance pole (conductor) to OPGW will be a vertical clearance.

CASE 1: Pole-to-Pole (if they are located in vertical configuration): 30 ft (w/3 ' buffer).
Pole-to-OPGW: 19 ft (w/3' buffer).The Vertical clearance at the structure shall be per NESC 235C. Reference NESC Table 235-5.

CASE 2: Pole-to-Pole (if they are located in vertical configuration): 30 ft (w/3' buffer).
Pole-to-OPGW: 19 ft (w/ 3' buffer). Vertical clearances at the structure shall be adjusted to provide sag-related clearances at any point in the span per NESC 235C.2.b. The sag-related clearances in the span are considered as diagonal clearances.

CASE 3: Galloping

Refer to section titled "Galloping".

Radial Clearance from Line Conductors to Supports, and to Vertical or Lateral Conductors, Span or Guy Wires Attached to the Same Support
NESC: To supports: 17.33' (MAD for Tools"12.33 per IEEE 516-2009+Working Space: 4.5' per NESC Rule 236&237)
To anchor guys: 19.4' (w/3 ft buffer) per NESC235E, 4 b., where 600 kV, dc equivalent to 735 kV ac.
The NESC Rule 235E3b (Alternative Clearances-600 kV DC): 16' and Rule 235E, 4b (600 kV dc equivalent to 735 KV ac): 16' do not control, it is the MAD for tools+WS:17.33' that controls this clearance case.
REA: N/A
Other: N/A

MISCELLANEOUS

Grounding Requirements (type and frequency of grounding required)

Ground Type:

Butt Plate:	N/A
Butt Wrap:	N/A
Ground Rod:	To be used.
Other:	

Frequency of Grounding:

All Structures:	Yes
No. Per Mile:	TBD
Maximum Resistance per Structure (ohms):	10
Other:	

Special Equipment

Describe any special equipment requirements (switches, fiber optic materials, distribution underbuild, reclosers, etc.):

Splice boxes for the OPGW fibers will be used at the splice structures where an OPGW reel will finish, and at certain dead-end structures. Underground loose tube (LT) type fiber optic cable will be used from the last structure to the substation. The fibers from this underground fiber optic cable will be spliced to the fibers from the OPGW inside the splice box located on the last structure before the substation.

Material

Describe Owner supplied material (attach additional sheets if necessary):

Does the utility have a standard material list it uses: YES ☐ NO ☐

Describe Contractor supplied material (attach additional sheets if necessary) :

Environmental Protection

State any measures required or agencies to be contacted for wildlife protection requirements:

Describe any known industrial, salt-water contamination or other environment that may impact or has been known to impact electrical insulation:

State any measures required for airborne contamination protection (dust control):

___

___

___

Describe any known caustic or corrosive soil conditions:

___

___

___

DRAWINGS AND MAPS

Maps

Existing facility maps, P&P's available: YES ☐ NO ☐

List foreign utilities to be considered for project, if maps are available:

Power:	___	Gas:	___
Phone:	___	TV:	___
Sewer:	___	Water:	___
Highways:	___	Railroad:	___
Other:	___		

Separate access road maps required: YES ☐ NO ☐
Describe ROW/Environmental or Easement Maps required, if any:

___

___

___

Drawing Requirements
Map and Plan and Profile Scales:

Key Map Scale: ___ **horiz.**

Plan Scale: ___ horiz.

Profile Scale: ___ vert. Size: ___ horiz.

Plan Type:

- Planimetric: ___
- Topographic: ___
- Other: ___

Title Block:

- POWER Standard: ___
- Other: ___

Drawing Numbers:

- POWER Generated: ___
- Owner Generated (describe): ___
- Final Drawings: ___

Describe structure numbering sequence:

Describe any controlling mapping specifications:
All coordinates will be based on various State Plane systems, as required. Vertical datum is based on NAVD 88.

SUSTATION/SWITCHYARD INTERFACE

Terminate at existing substation entry structure: YES ☐ NO
Comments:

Maximum allowable tensions for substation deadend:

Conductor: 5000 lbs (assumed, no station data available)
OPGW/OHGW: 3000 lbs (assumed, no station data available)

Attachment height above ground substation deadend:

Conductor: TBD (no station data available)
OPGW/OHGW: TBD (no station data available)

Are substation drawings available? YES ☐ NO ☐, (if so, include)

OTHER

Describe any other items the engineer/designer may need to know to complete this project (attach additional sheets if necessary):

Appendix A- Comparison of Clearances for Clean Line +/- 600 kV Project Grain Belt Express

Case	NESC- DC V nom=600 KV peak, pole-ground V max=632 KV (5% over V nom)	NESC- AC Equivalent V nom=735 KV rms, phase-to-phase 735=600*sqrt(3)/sqrt(2) Rule 230 H V max=772 KV (5% over V nom)	EPRI T/L Reference Book HVDC Lines	MAD* for Tools (IEEE 516-2009) + Working Space (NESC Rule 236& 237)	Conclusion: Minimum possible value that can be used
Conductor to Ground:	Rule 232 D.3:	Rule 232 B and 232 C:	Not addressed.	N/A	
a. Track rails of railroads	38.68' (bare) 39' (rounded) 42' (w/3' buffer)	40.6' (bare) 41' (rounded) 44' (w/3' buffer)			42'
b. Streets, Alleys, roads, driveways, and parking lots	30.68' (bare) 31' (rounded) 34' (w/3' buffer)	32.6' (bare) 33' (rounded) 36' (w/3' buffer)			34'
c. Spaces and ways subject to pedestrians or restricted traffic:	26.68' (bare) 27' (rounded) 30' (w/3' buffer)	28.6' (bare) 29' (rounded) 32' (w/3' buffer)			30'
d. Vehicular areas	30.68' (bare) 31' (rounded) 34' (w/3' buffer)	32.6' (bare) 33' (rounded) 36' (w/3' buffer)			34'
Conductor to Water:	Rule 232 D, Table 232-3:	Rule 232, Table 232-1:	Not addressed.	N/A	
e. Water areas not suitable for sail boating or where sail boating is prohibited	28.46' (bare) 29' (rounded) 32' (w/3' buffer)	31.1' (bare) 32' (rounded) 35' (w/3' buffer)			32'
f. Water areas suitable for sail boating, including rivers, lakes, ponds, canals with unobstructed surface area:					
1) less than 0.08 km^2 (20 acres)	31.96' (bare) 32' (rounded) 35' (w/3' buffer)	34.6' (bare) 35' (rounded) 38' (w/3' buffer)			35'
(2) over 0.08 to 0.8 km^2 (20 to 200 acres)	39.96' (bare) 40' (rounded) 43' (w/3' buffer)	42.6' (bare) 43' (rounded) 46' (w/3' buffer)			43'
3) over 0.8 to 8 km^2 (200 to 2000 acres)	45.96' (bare) 46' (rounded) 49' (w/3' buffer)	48.6' (bare) 49' (rounded) 52' (w/3' buffer)			49'
(4) over 8 km^2 (2000 acres) Mississippi River Crossing	51.96' (bare) 52' (rounded) 55' (w/3' buffer)	54.6' (bare) 55' (rounded) 58' (w/3' buffer)			55'

Case	**NESC- DC** V nom=600 KV peak, pole-ground V max=632 KV (5% over V nom)	**NESC- AC Equivalent** V nom=735 KV rms, phase-to-phase 735=600*sqrt(3)/sqrt(2) Rule 230 H V max=772 KV (5% over V nom)	**EPRI** T/L Reference Book HVDC Lines	**MAD* for Tools** (IEEE 516-2009) + **Working Space** (NESC Rule 236& 237)	**Conclusion:** Minimum possible value that can be used
Conductor to Structure No Wind	12.96' (bare) 13' (rounded) 16' (w/3 ' buffer) Rule 235 E.3b	12.95' (bare) 13' (rounded) 16' (w/3' buffer) Rule 235E, Table 235-6, item 4b	16.4' No Wind Case corresponds to Lightning Impulse, required clearance from Figure 10-13, page 150. Lightning Surge will be at least 30% higher than Switching Surge: 1080*1.3=1404 kV Surge Factor: Ti=1.8	12.83'+4.5'=17.33' MAD+WS	**17.33'**
Conductor to Structure Medium Wind 6 psf	12.96' (bare) 13' (rounded) 16' (w/3' buffer) Rule 235 E.3b	12.95' (bare) 13' (rounded) 16' (w/3' buffer) Rule 235E, Table 235-6, item 4b	9.8 ' Medium Wind Case corresponds to Switching Impulse, required clearance from Figure 10-13, page 150 Switching Surge=1.8*600 =1080 kV Surge Factor: Ti=1.8	12.83'+4.5'=17.33' MAD+WS	**17.33'**
Conductor to Structure Extreme Wind 24.3 psf	Not addressed	Not addressed	4.1' (no buffer) 5' (w/0.9' buffer) Extreme Wind corresponds to Steady State required clearance from Fig.10-3 , Page 145 and Fig.10-4, Page 146.	Not addressed	**5'**

*MAD=Minimum Approach Distance.

NESC-Clearance Conductor to Ground calculation:

NESC- DC:	**NESC- AC Equiv**
V nom=600 KV peak, pole-ground V max=632 KV (5% over V nom)	V nom=735 KV rms, phase-to-phase 735=600*sqrt(3)/sqrt(2) Rule 230 H V max=772 KV (5% over V nom)
Rule 232D, table 232-3: a. Track rails of railroads: H ref=22' b. Streets, Alleys, roads, driveways, and parking lots: H ref=14' c. Spaces and ways subject to pedestrians or restricted traffic: H ref=10' d. Vehicular areas: H ref=14' For Ref Altitude < 1500 ft: V max=1.05*V nom=632 kV C ref=3.28*(632*1.8*1.15/(500*1.15)^1.667*1.03*1.2=15.96' For assumed maximum altitude for this line (worst case scenario): 3000 ft: Altitude Adder: (3000'-1500')/1000'*3%=4.5% C alt=C ref*1.045=15.96'*1.045=16.68' a. Track rails of railroads: C total=H ref + C alt=22' + 16.68'=**38.68' (bare)** **39' (rounded)** **42' (w/3' buffer)** **CHOSEN** b. Streets, Alleys, roads, driveways, and parking lots: C total=H ref + C alt=14' + 16.68'=**30.68' (bare)** **31' (rounded)** **34' (w/3' buffer)** **CHOSEN** c. Spaces and ways subject to pedestrians or restricted traffic: C total=H ref + C alt=10' + 16.68'=**26.68' (bare)** **27' (rounded)** **30' (w/3' buffer)** **CHOSEN** d. Vehicular Areas: C total=H ref + C alt=14' + 16.68'=**30.68' (bare)** **31' (rounded)** **34' (w/3' buffer)** **CHOSEN**	Equivalent max ac system voltage=735*1.05=772 KV Equivalent max ac system voltage, phase-to-ground=772/sqrt(3)=446 kV NESC Rule 232, Table 232-1, open supply conductor up to 22 kv: a. Track rails of railroads: H basic=26.5' b. Streets, Alleys, roads, driveways, and parking lots: H basic=18.5' c. Spaces and ways subject to pedestrians or restricted traffic: H basic=14.5' d. Vehicular areas: H basic=18.5' Voltage Adder: C adder=(446-22)*0.4"/12=14.1' Altitude adder : zero a. Track rails of railroads: C total=H basic + C adder= 26.5' + 14.1'=**40.6' (bare)** **41' (rounded)** **44' (w/3' buffer)** b. Streets, Alleys, roads, driveways, and parking lots: C total=H basic + C adder= 18.5' + 14.1'=**32.6' (bare)** **33' (rounded)** **36' (w/3' buffer)** c. Spaces and ways subject to pedestrians or restricted traffic : C total=H basic + C adder= 14.5' + 14.1'=**28.6' (bare)** **29' (rounded)** **32' (w/3' buffer)** d. Vehicular Areas: C total=H basic + C adder= 18.5' + 14.1'=**32.6' (bare)** **33' (rounded)** **36' (w/3' buffer)**

NESC- Clearance Conductor-to-Structure calculation
for Cases: Medium Wind (6 psf) and No Wind:

NESC- DC:	NESC- AC Equiv
V nom=600 KV peak, pole-ground V max=632 KV (5% over V nom)	V nom=735 KV rms, phase-to-phase 735=600*sqrt(3)/sqrt(2) Rule 230H V max=772 KV (5% over V nom)
Rule 235E3b For Ref Altitude < 1500 ft: V max=1.05*V nom=632 kV C ref=39.37*(632*1.8*1.15/(500*1.2)^1.667*1.03=148.7"=12.4' For assumed maximum altitude for this line (worst case scenario): 3000 ft: Altitude Adder: (3000'-1500')/1000'*3%=4.5% C alt=C ref*1.045=12.4'*1.045=12.96' C alt=**12.96' (bare)** **13' (rounded)** **16' (w/3' buffer)** **CHOSEN**	Equivalent max ac system voltage=735*1.05=772 KV Equivalent max ac system voltage, phase-to-ground=772/sqrt(3)=446 kV NESC Rule 235 E, 4b, open supply conductor up to 50 kv: H basic=11"=0.917' Voltage Adder: C adder=(772-50)*0.2"/12=12.033' Altitude adder : zero C total=H basic + C adder= 0.917' + 12.033'=**12.95' (bare)** **13' (rounded)** **16' (w/3' buffer)**

NESC- Clearance to Anchor Guys calculation:
for Cases: Medium Wind (6 psf) and No Wind:

NESC- AC Equiv
V nom=735 KV rms, phase-to-phase 735=600*sqrt(3)/sqrt(2) Rule 230H V max=772 KV (5% over V nom)
Equivalent max ac system voltage=735*1.05=772 KV Equivalent max ac system voltage, phase-to-ground=772/sqrt(3)=446 kV NESC Rule 235 E, 4b, open supply conductor up to 50 kv: H basic=16"=1.333' Voltage Adder: C adder=(772-50)*0.25"/12=15.041' Altitude adder : zero C total=H basic + C adder= 1.333' + 15.041'=**16.374' (bare)** **16.4' (rounded)** **19.4 ' (w/3' buffer)** **CHOSEN**

NESC-Clearance to Right -of-Way (Blowout):
for Cases: Medium Wind (6 psf) and No Wind:

NESC- AC Equiv
V nom=735 KV
rms, phase-to-phase
735=600*sqrt(3)/sqrt(2)
Rule 230H
V max=772 KV
(5% over V nom)

Equivalent max ac system voltage=735*1.05=772 KV
Equivalent max ac system voltage, phase-to-ground=772/sqrt(3)=446 kV
NESC Rule 234B, clearance to buildings, open supply conductor up to 22 kv:
H basic=4.5' **(with 6 psf wind)**
H basic=7.5' **(with no wind)**

Voltage Adder: C adder=(446-22)*0.4"/12=14.133'
Altitude adder : zero

Medium Wind (6 psf):
C total=H basic + C adder= 4.5' + 14.133'=**18.633' (bare)**
19' (rounded)
22' (w/3' buffer)
CHOSEN

No Wind (0 psf):
C total=H basic + C adder= 7.5' + 14.133'=**21.633' (bare)**
22' (rounded)
25' (w/3' buffer)
CHOSEN

NESC- Clearance Conductor-to-Water calculation

NESC- DC:	**NESC- AC Equiv**
V nom=600 KV peak, pole-ground V max=632 KV (5% over V nom)	V nom=735 KV rms, phase-to-phase 735=600*sqrt(3)/sqrt(2) Rule 230H V max=772 KV (5% over V nom)
Rule 232D, Table 232-3 item: e. Water areas not suitable for sail boating or where sail boating is prohibited: H ref=12.5' f. Water areas suitable for sail boating, including rivers, lakes, ponds, canals with unobstructed surface area: (1) less than 0.08 km^2 (20 acres): H ref=16' (2) over 0.08 to 0.8 km^2 (20 to 200 acres): H ref=24' (3) over 0.8 to 8 km^2 (200 to 2000 acres): H ref=30' (4) over 8 km^2 (2000 acres): Mississippi River Crossing: H ref=36' For Ref Altitude < 1500 ft: V max=1.05*V nom=632 kV C ref=3.28*(632*1.8*1.15/(500*1.15)^1.667*1.03*1.2=15.96' PU=1.8-maximum switching surge factor for +/- 600 kV DC Altitude at Mississippi River Crossing location: Alt=300' from PLS-CADD Model 300' < 1500' results: Altitude Adder=0, results: C alt=C ref=15.96' e. Water areas not suitable for sail boating or where sail boating is prohibited: C total=H ref+C alt=12.5'+15.96'=**28.46' (bare)** **C total=29' (rounded)** **C total=32' (w/3' buffer)** **CHOSEN** f. Water areas suitable for sail boating, including rivers, lakes, ponds, canals with unobstructed surface area: (1) less than 0.08 km^2 (20 acres): C total=H ref+C alt=16'+15.96'=**31.96' (bare)** **C total=32' (rounded)** **C total=35' (w/3' buffer)** **CHOSEN** (2) over 0.08 to 0.8 km^2 (20 to 200 acres): C total=H ref+C alt=24'+15.96'=**39.96' (bare)** **C total=40' (rounded)** **43' (w/3' buffer)** **CHOSEN** (3) over 0.8 to 8 km^2 (200 to 2000 acres): C total=H ref+C alt=30'+15.96'=**45.96' (bare)** **C total=46' (rounded)** **49' (w/3' buffer)** **CHOSEN** (4) over 8 km^2 (2000 acres): Mississippi River Crossing: C total=H ref+C alt=36'+15.96'=**51.96' (bare)**	Equivalent max ac system voltage=735*1.05=772 KV Equivalent max ac system voltage, phase-to-ground=772/sqrt(3)=446 kV NESC Rule 232, Table 232-1, open supply conductor up to 22 kV: 6. Water areas not suitable for sail boating or where sail boating is prohibited: H basic=17' 7. Water areas suitable for sail boating, including rivers, lakes, ponds, canals with unobstructed surface area: (1) less than 0.08 km^2 (20 acres): H basic=20.5' (2) over 0.08 to 0.8 km^2 (20 to 200 acres): H basic=28.5' (3) over 0.8 to 8 km^2 (200 to 2000 acres): H ref=34.5' (4) over 8 km^2 (2000 acres): Mississippi River Crossing: H ref=40.5' Voltage Adder: C adder=(446-22)*0.4"/12=14.1' Altitude at Mississippi River Crossing location: Alt=300' from PLS-CADD Model 00' < 1500' results: Altitude Adder=0, results: C alt=C adder=14.1' e. Water areas not suitable for sail boating or where sail boating is prohibited: C total=H basic + C adder= 17' + 14.1'=**31.1' (bare)** **C total=32' (rounded)** **C total=35' (w/3' buffer)** f. Water areas suitable for sail boating, including rivers, lakes, ponds, canals with unobstructed surface area: (1) less than 0.08 km^2 (20 acres): C total=H basic + C adder= 20.5' + 14.1'=**34.6' (bare)** **C total=35' (rounded)** **C total=38' (w/3' buffer)** (2) over 0.08 to 0.8 km^2 (20 to 200 acres): C total=H basic + C adder= 28.5' + 14.1'=**42.6' (bare)** **C total=43' (rounded)** **C total=46' (w/3' buffer)** (3) over 0.8 to 8 km^2 (200 to 2000 acres): C total=H basic + C adder= 34.5' + 14.1'=**48.6' (bare)** **C total=49' (rounded)** **C total=52' (w/3' buffer)** 4) over 8 km^2 (2000 acres): Mississippi River Crossing: C total=H basic + C adder= 40.5' + 14.1'=**54.6' (bare)**

C total=52' (rounded) 55' (w/3' buffer) CHOSEN	C total=55' (rounded) C total=58' (w/3' buffer)

Appendix B-OPGW Detailed Specification:

This +/-600 kV DC line will go through Kansas and Missouri, and according to the Visalia public domain Ground Flash Density (GFD) Map (http://www.weather.gov/os/lightning/images/Vaisala_96-05_Flash_Map.gif), the expected average maximum GFD in these regions is about GFD max= 6 [strokes/sqkm/year]. This is a significant value, enough to require a lower maximum allowable shielding angle. For this project, we have selected 15 degrees.

For an GFD=6 [strokes/sqkm/year], and considering, at this preliminary design criteria stage, an average tower height of 42 m=140 ft, and a distance between the 2 OPGWs of about 8.8 m = 29 ft, and assuming the average ruling span at 460 m=1500 ft, for an exposure interval of 30 years, and assuming 95% of the lightning strikes are negative and 5% are positive (which is a typical case) results the worst lightning charge to be **Q=121 Coulombs (negative polarity)**, using IEEE 1243 method.

That will require the OPGW to have in the outer layer a wire diameter of minimum **3.1 mm (ACS 20.3%IACS wire material).** Calculations of required outer wire diameter based on formulas developed empirically from test data developed by AFL.

This minimum size of wire in the outer layer: **3.1 mm** is necessary to ensure that after lightning strike, the remaining strength in the OPGW will be at least 75% of the original OPGW RBS, per IEEE 1138 OPGW lightning test method.

See attached calculations prepared by Power Engineers in "Lightning Algorithm-Clean Line-Expected Charge .xlsx" Spreadsheet, that is attached as Appendix C to this Preliminary Design Criteria.

Also, because this line will be in a region with 1.25" ice with concurrent wind of 4.1 psf (NESC), a good assumption is that the OPGW maximum working tension will be at about 60%RBS under 1.25" ice+4.1 psf wind, in order for the OPGW sag to be at 85% of the conductor sag at 60 F, Final, bare cable.

Therefore, the OPGW must have **Cable Tension for Zero Fiber Strain (CTZFS) of at least 85%RBS**. Due to this requirement any OPGW with central tube design (i.e. fibers in central stainless steel tube, or fibers in central stainless steel tube inside an aluminum pipe), are not recommended.

These types of designs do not meet CTZFS=85%RBS.
At this level of high tension, in this type of design, there will be some allowable fiber strain, about 0.20%-0.33%, which can result in fiber attenuation [dB/km].

The only OPGW design that will meet Cable Tension for Zero Fiber Strain (CTZFS)=85%RBS is a stranded stainless steel tube design, where the fibers are located inside stranded stainless steel tubes.
The fibers need to be in an element that has a lay length (pitch), because the EFL (Excess Fiber Length) itself inside the tube is not sufficient to provide CTZFS=85%RBS.

Minimum EFL (Excess Fiber Length) in the stainless steel tube must be 0.5%, and the lay length (pitch) of the inner layer, containing the stainless steel tubes, must be tight enough to obtain enough fiber free elongation in tension to reach CTZFS=85%RBS.

Therefore, it is recommended that the inner layer lay ratio be in the range of 10-13.
This means that the inner layer lay length (pitch) must be 10 to 13 times the diameter over the inner layer.

The preferred design, for maximum 48 fibers, will be a design with 2 stainless steel tubes in the inner layer, each with a maximum of 24 fibers.

If more than 12 fibers per tube are used, the fibers will be grouped in 12 fibers, each group of 12 fibers should be differentiated using stripes, not string binders.

Note that while an OPGW design with fibers inside stranded plastic buffer tubes inside an AL Pipe will also meet the requirement of CTZFS = 85%RBS. However, an OPGW designed in this manner will be much larger (with a resulting increase in structure loads) than an equivalent design using stranded stainless steel tubes designs.

The OPGW Rated breaking Strength (RBS) will be calculated as 90% of the OPGW UTS (Ultimate Tensile Strength), as defined in IEEE 1138 standard for OPGW.

The hollow stainless steel tubes will not be considered in the calculation of the OPGW RBS, only the wires.

The type of fiber to be used, due to the line length: 800 miles, must be G.655C (NZDSF=Non-Zero Dispersion Shifted Fiber, large Core Area), and not SMF G.652D (Low Water Peak).

Using G.655C type of fibers allows an increased spacing between repeaters (amplifiers) to reduce the non-linear effects, which determines fiber losses (fiber attenuation, in dB/km).

The G.655 fibers attenuation limits should be:

- 0.22 db/km @ 1550 nm
- 0.25 dB/km @ 1625 nm

Important Note: these will be the "cabled" fiber maximum allowed attenuation values, not the "uncabled" fibers value (incoming fiber from fiber's manufacturer).

Based on the above, the preliminary OPGW design characteristics/specifications are as follows: Maximum Cable Diameter: D c=0.591 inches

- Minimum Wire Diameter in the Outer Layer: D wire=3.00 mm
- Maximum Weight: W=0.475 lbs/ft
- Minimum Rated Breaking Strength: RBS=25369 lbs
- Minimum Cable Tension for Zero Fiber Strain=85%RBS
- Minimum Total Cross-Sectional Area: A=0.19 sq in
- Minimum Fault Current Rating: I^2*t=98 kA^2*sec; which corresponds to the following assumed fault magnitude and clearing time scenarios:
  - I=14.0 kA; t=0.50 sec (worst case scenario: longest fault current duration: 30 cycles)
  - I=31.3 kA; t=0.10 sec (best case scenario: shortest fault current duration: 10 cycles) (fault current: initial temperature=40 C; final temperature=210 C)
- Maximum DC Resistance at 20 deg C: R dc=0.7945 Ohm/mile
- Outer Layer of Wire Lay Direction: Left
- Fiber Type: G.655C: fiber attenuation limits: 0.22 dB/km @ 1550 nm; 0.25 dB/km @ 1625 nm.
- Fiber Count: Minimum: 12; Maximum 48
- PLS-CADD .wir file: polynomial coefficients from SAG10 chart 1-1427

Algorithm To Establish Calculated Lightning Charge Levels at Customer Location:

This spreadsheet to be used ONLY when customer DID NOT provide lightning charge level in his technical specifications, and that lightning charge level must be established at customer location.

Line Geometry Input:

1. Tower Height: h_t **42** [m] **Note:** **"h_t" should be provided by customer.**

ONLY if the customer does not know the tower height: h t , it can be assumed:

for Distribution Lines, 0 kV < V <= 69 kV:	h_t =	25	[m]
for Transmission Lines, 69 kV < V <= 115 kV:	h_t =	30	[m]
for Transmission Lines, 115 kV < V <= 230 kV:	h_t =	35	[m]
for Transmission Lines, 230 kV < V <= 345 kV:	h_t =	40	[m]
for Transmission Lines, 345 kV < V <= 1000 kV:	h_t =	45	[m]

2. Number of Groundwires: N_{GW} **2** [-] **Note:** **"N_{GW}" should be provided by customer.**

3. Groundwires Spacing: b **8.8** [m] **Note:** **"b" should be provided by customer.**
if 2 groundwires: $N_{GW} = 2$, then "b" has a value
if 1 groundwire: $N_{GW} = 1$, then "b" = 0

ONLY if the customer does not know the spacing between the 2 groundwires: b, it can be assumed:

for Distribution Lines, 0 kV < V <= 69 kV:	b =	2	[m]
for Transmission Lines, 69 kV < V <= 115 kV:	b =	3	[m]
for Transmission Lines, 115 kV < V <= 230 kV:	b =	4	[m]
for Transmission Lines, 230 kV < V <= 345 kV:	b =	5	[m]
for Transmission Lines, 345 kV < V <= 1000 kV:	b =	6	[m]

4. Average Span: S **457** [m] **Note:** **"S" should be provided by customer.**

ONLY if the customer does not know the average span: S, of that line, it can be assumed:

for Distribution Lines, 0 kV < V <= 69 kV:	S =	100	[m]
for Transmission Lines, 69 kV < V <= 115 kV:	S =	225	[m]
for Transmission Lines, 115 kV < V <= 230 kV:	S =	275	[m]
for Transmission Lines, 230 kV < V <= 345 kV:	S =	300	[m]
for Transmission Lines, 345 kV < V <= 1000 kV:	S =	325	[m]

5. Line Length: L **30** [km] **Note:** **"L" should be provided by customer.**

Meteorological Input:

1. Ground Flash Density: N_g 1.15 **[strokes/km^2/year] (also called : GFD) ; GFDline=GFD^0.078=6^0.078=1.15**

Notes:
1. For USA: use the GFD map from spreadsheets: "Vidalia" **OR "USA GFD Map- Global Atmospherics" (this one is more detailed)**
2. For Canada: use the GFD map from spreadsheet "**Canada GFD Map-CEA**".
3. For South Africa: use the GFD map from spreadsheet **"South Africa GFD Map-CSIR"**.
4. For the rest of the world: use 10% of the total OTD data from the the web site provided in the spreadsheet **"Rest of the World"**.

Reason:
OTD data: only 10% are flashes cloud -to- ground (the one you are interested in: GFD)
the rest 90% are flashes cloud-to-cloud or intracloud (you are not interested in these data)

2. Precent Negative Flashes (PNF) in the total number of flashes:

PNF= 0.95 **[probability, absolute value]**

Note: **if not known from OTD data, it can be used as default: PNF= 0.95 (95%).**

3. Precent Positive Flashes (PPF) in the total number of flashes:

PPF= 0.05 **[probability, absolute value]**

Note: **if not known from OTD data, it can be used as default: PNF= 0.05 (5%).**

Probability Input:

Exposure Interval: **Y** 30 **[years]**

Important Check: $Y \cdot L \cdot N_g$ 1035 **[strokes/km]** O.K.

Note: **The product: "Y*L*Ng" MUST be MAXIMUM** 4000 **[strokes/km]**

Reason for the product "Y*L*Ng" limitation: **for long lines cases, to avoid level of charges too high, resulting in OPGW design cost prohibitive.**

Calculations (Output Data):

1. **Total Number of Flashes to the Line**: N_{Line}:

Ericsson's formula: $N_{Line} = 0.10 \cdot N_g \cdot (28 \cdot h_t^{0.6} + b)$ [strikes/100 km/year]

where: R $R_a = 14 \cdot h_t^{0.6}$ a = attractive radius [m]

$N_{Line} =$ 31 [strikes/100 km/year]

2. **Total Number of Flashes to the Tower**: N_{tower}:

IEEE proposed formula: $N_{tower} = \frac{b}{S} \cdot N_{Line}$ [strikes/100 km/year]

$N_{tower} =$ 0 [strikes/100 km/year]

3. **Total Number of Flashes to the OPGW**: N_{OPGW}:

IEEE proposed formula: $N_{OPGW} = \frac{N_{Line} - N_{tower}}{N_{GW}}$ [strikes/100 km/year]

$N_{OPGW} =$ 15 [strikes/100 km/year]

4. **Basic Probability Level for stroke current, rate of rise and total flash charge:** P:

IEEE proposed formula: $P = \frac{100}{Y \cdot L \cdot N_{OPGW}}$ [probability, absolute value]

$P =$ 0.0074 [probability, absolute value]

0.74 [probability,precent]

5. Probability Design Level for Negative First Stroke Flashes: P_{first}^{neg}

IEEE proposed formula: $P_{first}^{neg} = \frac{P}{PNF}$ **[probability, absolute value]**

$P_{first}^{neg} =$ **0.0078** **[probability, absolute value]**

0.78 **[probability, precent]**

6. Corresponding Number of Negative Flashes to this Probability Design Level: **NNF:**

IEEE proposed formula: $NNF = \frac{1}{P_{first}^{neg}}$ **128** **[negative flashes]**

5. Probability Design Level for Positive First Stroke Flashes: P_{first}^{pos}

IEEE proposed formula: $P_{first}^{pos} = \frac{P}{PPF}$ **[probability, absolute value]**

$P_{first}^{pos} =$ **0.1481** **[probability, absolute value]**

14.81 **[probability, precent]**

6. Corresponding Number of Positive Flashes to this Probability Design Level: **NPF:**

IEEE proposed formula: $NPF = \frac{1}{P_{first}^{pos}}$ **7** **[positive flashes]**

7. Negative First Stroke Peak Amplitude: $I_{first}^{neg\,*}$

probabilistic function: **log normal:**

IEEE formula: $P_{(I>I^*)} = \frac{1}{1+\left(\frac{I^*}{31}\right)^{2.6}}$ **where:** $I_m = 31 \quad [kA]$ **median current for negative first stroke**

$$I_{first}^{neg*} = 31 \cdot \left(\left(P_{first}^{neg}\right)^{-1} - 1\right)^{\frac{1}{2.6}}$$ [kA]

$I_{first}^{neg\,*} =$ **200** [kA]

8. Positive First Stroke Peak Amplitude: $I_{first}^{pos\,*}$

probabilistic function: **log normal:**

IEEE formula: $P_{(I>I^*)} = \frac{1}{1+\left(\frac{I^*}{31}\right)^{2.6}}$ **where:** $I_m = 31 \; [kA]$ **median current for positive first stroke**

$$I_{first}^{pos*} = 31 \cdot \left(\left(P_{first}^{pos}\right)^{-1} - 1\right)^{\frac{1}{2.6}}$$ [kA]

$I_{first}^{pos\,*} =$ 61 [kA]

9. Negative Subsequent Strokes Probability: P_{subs}^{neg}

Typically: 2 subsequent strokes for every first stroke:

IEEE formula: $P_{subs}^{neg} = \frac{P_{first}^{neg}}{2}$ **[probability, absolute value]**

$P_{subs}^{neg} =$ 0.0039 **[probability, absolute value]**

0.39 **[probability, precent]**

10. Negative Subsequent Strokes Peak Amplitude: $I_{subs}^{neg\,*}$

IEEE formula:

$P_{(I>I^*)} = \frac{1}{1+\left(\frac{I^*}{12}\right)^{2.7}}$ **where:** $I_m = 12 \; [kA]$ **median current for negative subsequent strokes**

$$I_{subs}^{neg*} = 12 \cdot \left(\left(P_{subs}^{neg}\right)^{-1} - 1\right)^{\frac{1}{2.7}}$$ [kA]

$I_{subs}^{neg\,*} =$ 93 [kA]

11. Positive Subsequent Strokes Probability: P^{pos}_{subs}

Typically: 2 subsequent strokes for every first stroke:

IEEE formula: $P^{pos}_{subs} = \frac{P^{pos}_{first}}{2}$ **[probability, absolute value]**

$P^{pos}_{subs} =$ **0.0741** **[probability, absolute value]**

7.41 **[probability, precent]**

12. Positive Subsequent Strokes Peak Amplitude: $I^{pos\,*}_{subs}$

IEEE formula:

$P_{(I>I^*)} = \frac{1}{1+\left(\frac{I^*}{12}\right)^{2.7}}$ **where:** $I_m = 12 \quad [kA]$ **median current for for positive subsequent strokes**

$$I^{pos*}_{subs} = 12 \cdot \left(\left(P^{pos}_{subs}\right)^{-1} - 1\right)^{\frac{1}{2.7}}$$ [kA]

$I^{pos\,*}_{subs} =$ **31** [kA]

13. Negative Flash Total Charge: $Q_{negative}$

probabilistic function: log-normal:

Berger's curve for negative flashes: $P_{(Qnegative)} = \frac{1}{1+\left(\frac{Q_{negative}}{7}\right)^{1.7}}$ **where:** $Q_{negative\ med} = 7 \quad [C]$ **median charge value for negative flashes in Berger's curve**

$$Q_{negative} = 7 \cdot \left(\left(P^{neg}_{first}\right)^{-1} - 1\right)^{\frac{1}{1.7}}$$

$Q_{negative} =$ **121** [C]

14. Positive Flash Total Charge: $Q_{positive}$

probabilistic function: log-normal:

Berger's curve for positive flashes:

$$P_{(Q_{positive})} = \frac{1}{1+\left(\frac{Q_{positive}}{85}\right)^{2.0}}$$

where: $Q_{positive\ med} = 85\ [C]$ **median charge value for positive flashes in Berger's curve**

$$Q_{positive} = 85 \cdot \left(\left(P_{first}^{pos}\right)^{-1} - 1\right)^{\frac{1}{2.0}}$$

$Q_{positive} =$ **204** [C]

Note: Qpositive<2*Qnegative, TEST WILL BE DONE ONLY FOR Qnegative

Theoretical Requirements:

Total Negative Charge:

$Qnegative$ 121 [C]

First Stroke:

Peak Amplitude: $I_{first}^{neg\,*} =$ 200 [kA] **Rise Time:** $t_r =$ 1.2 [μsec] **Pulse Duration:** (Time to a half of the Amplitude) $t_d =$ 50 [μsec]

2 Subsequent Strokes:

Peak Amplitude: $I_{subs}^{neg\,*} =$ 93 [kA] **Rise Time:** $t_r =$ 0.1 [μsec] **Pulse Duration:** (Time to a half of the Amplitude) $t_d =$ 10 [μsec]

Note:
Between first stroke and the 2 subsequent strokes, there could be any combination of intermediate current component "B" and continuing current component "C", as long as the total charge remains:

$Q_{negative} =$ 121 [C]

Test Variables:

Total Negative Charge: $Q_{negative} =$ 121 [C]

If Test done ONLY with the intermediate component "B" and the continuing component "C":

intermediate component "B":			**continuous component "C":**		
charge:	$Q_B =$	10 [C]	**charge:**	$Q_C =$	111 [C]
mean current:	$I_{B\,mean} =$	2000 [A]	**current:**	$I_C =$	250 [A]
time:	$t_B =$	0.005 [sec]	**time:**	$t =$	0.444 [sec]

Theoretical Requirements:

Total Positive Charge:

$Q_{positive}$ = 204 [C]

First Stroke:

Peak Amplitude: I^{pos*}_{first} = 61 [kA] **Rise Time:** t_r = 1.2 [μsec] **Pulse Duration: (Time to a half of the Amplitude)** t_d = 50 [μsec]

2 Subsequent Strokes:

Peak Amplitude: I^{pos*}_{subs} = 31 [kA] **Rise Time:** t_r = 0.1 [μsec] **Pulse Duration: (Time to a half of the Amplitude)** t_d = 10 [μsec]

Note:
Between first stroke and the 2 subsequent strokes, there could be any combination of intermediate current component "B" and continuing current component "C", as long as the total charge remains:

$Q_{positive}$ = 204 [C]

Test Variables:

Total Positive Charge: $Q_{positive}$ = 204 [C]

If Test done ONLY with the intermediate component "B" and the continuing component "C":

intermediate component "B":			continuous component "C":		
charge:	Q_B =	10 [C]	charge:	Q_C =	194 [C]
mean current:	$I_{B\ mean}$ =	2000 [A]	current:	I_C =	250 [A]
time:	t_B =	0.005 [sec]	time:	t =	0.775 [sec]

Wire Type: AW20.3% (all wires) **Tensile Strength: TS:** 195 [kpsi] **Conductivity: λ:** 20.3 [%]

Gap: 5 [cm] **Tolerance:** + / - 1 cm

Input below Total Charge from Customer Technical Specifications.

If is not provided, please follow the algorithm from spreadsheet "Calculated Charge" to determine the total charge at customer location, and then input below.

Note: only if positive charge is twice as large as the negative charge, there will be a test also for the positive charge, and you input the positive charge below.

Otherwise, positive charge does not matter.

Remnant Strength: 75 [%] RBS

Negative polarity: Q 121 [C] **Positive polarity: Q** 242 [C]

Wire Diameter: D 3.12 [mm] **Wire Diameter: D** 3.12 [mm]

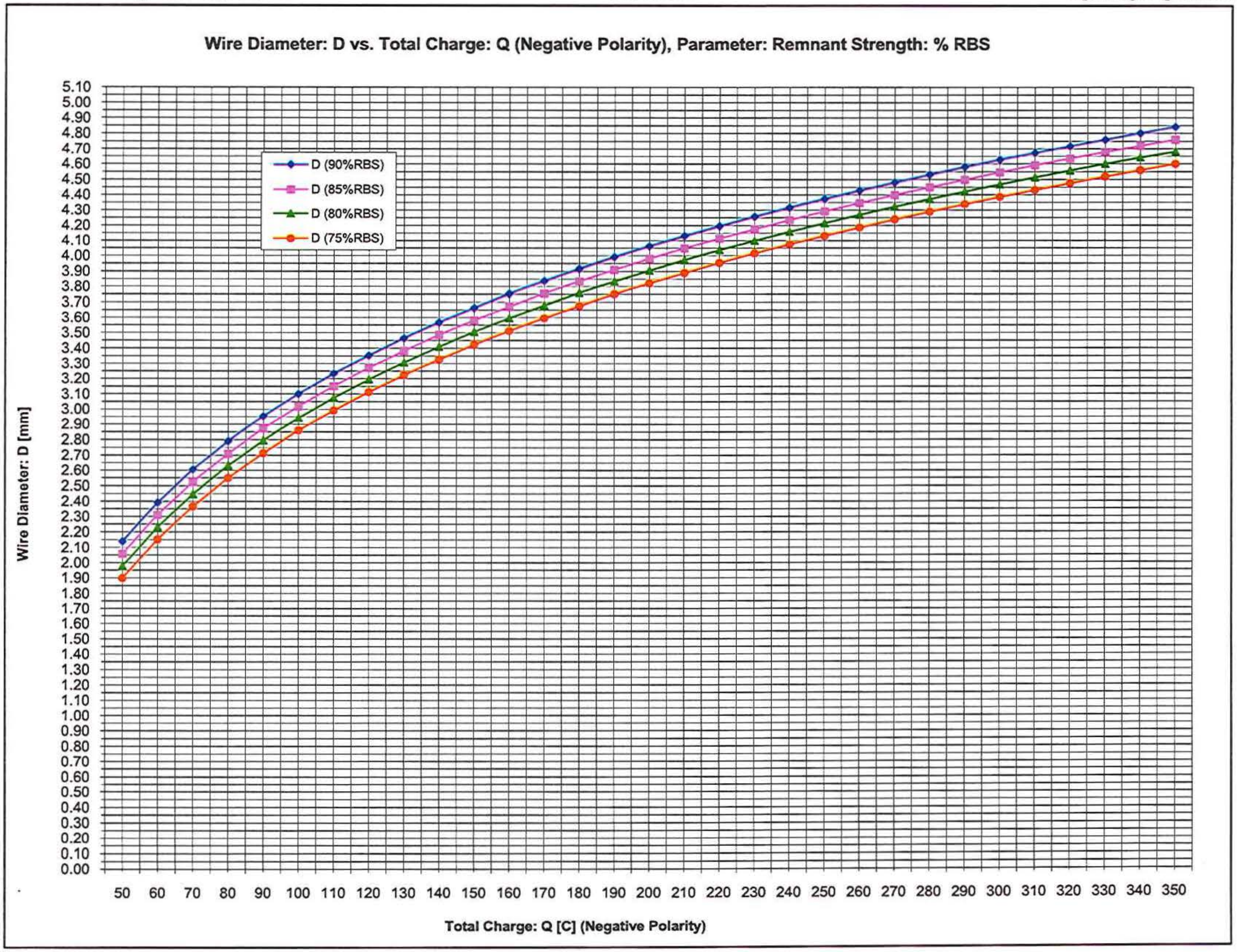
RBS= Rated Breaking Strength of the cable, NOT of the individual wire

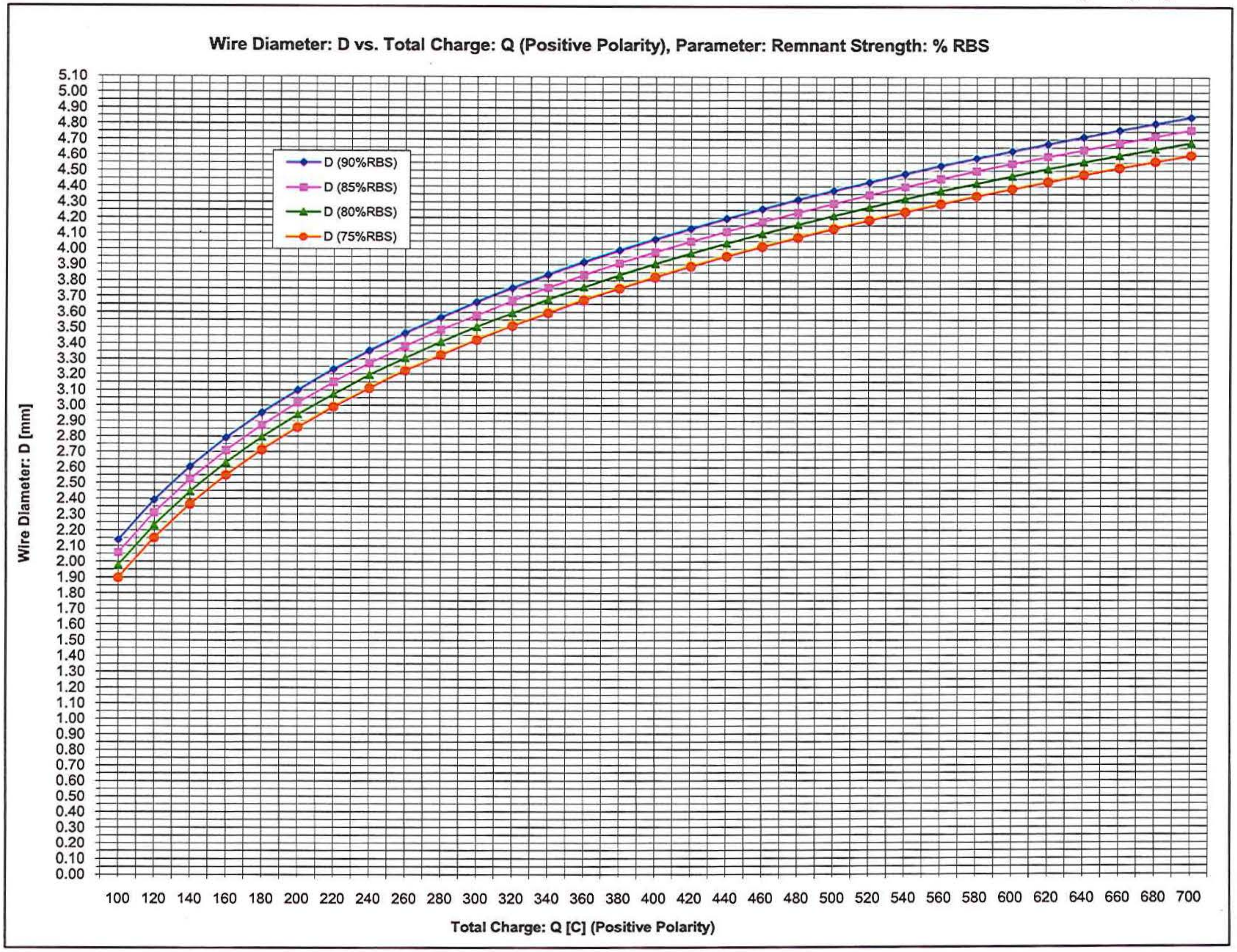
Negative Polarity:

Q	D (90%RBS)	D (85%RBS)	D (80%RBS)	D (75%RBS)
[C]	[mm]	[mm]	[mm]	[mm]
50	2.14	2.06	1.98	1.90
60	2.39	2.31	2.23	2.15
70	2.60	2.52	2.44	2.36
80	2.79	2.71	2.63	2.55
90	2.95	2.87	2.79	2.71
100	3.10	3.02	2.94	2.86
110	3.23	3.15	3.07	2.99
120	3.35	3.27	3.19	3.11
130	3.46	3.38	3.30	3.22
140	3.57	3.49	3.41	3.33
150	3.66	3.58	3.50	3.42
160	3.75	3.67	3.59	3.51
170	3.84	3.76	3.68	3.60
180	3.92	3.84	3.76	3.68
190	3.99	3.91	3.83	3.75
200	4.06	3.98	3.90	3.82
210	4.13	4.05	3.97	3.89
220	4.20	4.12	4.04	3.96
230	4.26	4.18	4.10	4.02
240	4.32	4.24	4.16	4.08
250	4.37	4.29	4.21	4.13
260	4.43	4.35	4.27	4.19
270	4.48	4.40	4.32	4.24
280	4.53	4.45	4.37	4.29
290	4.58	4.50	4.42	4.34
300	4.63	4.55	4.47	4.39
310	4.67	4.59	4.51	4.43
320	4.72	4.64	4.56	4.48
330	4.76	4.68	4.60	4.52
340	4.80	4.72	4.64	4.56
350	4.84	4.76	4.68	4.60

Positive Polarity:

Q	D (90%RBS)	D (85%RBS)	D (80%RBS	D (75%RBS)
[C]	[mm]	[mm]	[mm]	[mm]
100	2.14	2.06	1.98	1.90
120	2.39	2.31	2.23	2.15
140	2.60	2.52	2.44	2.36
160	2.79	2.71	2.63	2.55
180	2.95	2.87	2.79	2.71
200	3.10	3.02	2.94	2.86
220	3.23	3.15	3.07	2.99
240	3.35	3.27	3.19	3.11
260	3.46	3.38	3.30	3.22
280	3.57	3.49	3.41	3.33
300	3.66	3.58	3.50	3.42
320	3.75	3.67	3.59	3.51
340	3.84	3.76	3.68	3.60
360	3.92	3.84	3.76	3.68
380	3.99	3.91	3.83	3.75
400	4.06	3.98	3.90	3.82
420	4.13	4.05	3.97	3.89
440	4.20	4.12	4.04	3.96
460	4.26	4.18	4.10	4.02
480	4.32	4.24	4.16	4.08
500	4.37	4.29	4.21	4.13
520	4.43	4.35	4.27	4.19
540	4.48	4.40	4.32	4.24
560	4.53	4.45	4.37	4.29
580	4.58	4.50	4.42	4.34
600	4.63	4.55	4.47	4.39
620	4.67	4.59	4.51	4.43
640	4.72	4.64	4.56	4.48
660	4.76	4.68	4.60	4.52
680	4.80	4.72	4.64	4.56
700	4.84	4.76	4.68	4.60


Wire Diameter: D vs. Total Charge: Q (Negative Polarity), Parameter: Remnant Strength: % RBS
D (90%RBS)
D (85%RBS)
D (80%RBS)
D (75%RBS)
Wire Diameter: D [mm]
5.10
5.00
4.90
4.80
4.70
4.60
4.50
4.40
4.30
4.20
4.10
4.00
3.90
3.80
3.70
3.60
3.50
3.40
3.30
3.20
3.10
3.00
2.90
2.80
2.70
2.60
2.50
2.40
2.30
2.20
2.10
2.00
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300 310 320 330 340 350
Total Charge: Q [C] (Negative Polarity)


Wire Diameter: D vs. Total Charge: Q (Positive Polarity), Parameter: Remnant Strength: % RBS
D (90%RBS)
D (85%RBS)
D (80%RBS)
D (75%RBS)
Wire Diameter: D [mm]
5.10
5.00
4.90
4.80
4.70
4.60
4.50
4.40
4.30
4.20
4.10
4.00
3.90
3.80
3.70
3.60
3.50
3.40
3.30
3.20
3.10
3.00
2.90
2.80
2.70
2.60
2.50
2.40
2.30
2.20
2.10
2.00
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400 420 440 460 480 500 520 540 560 580 600 620 640 660 680 700
Total Charge: Q [C] (Positive Polarity)

Formulas:

RBS= Rated Breaking Strength of the cable, NOT of the individual wire

Negative Polarity:

For Remanent Strength=90% RBS:

$$D=0.144702564\frac{TS}{\lambda}\cdot\ln\left(0.001041026\frac{TS}{\lambda}\cdot Q\right)+3.10$$

$$D=1.39\ln(0.01\cdot Q)+3.10$$

For Remanent Strength=85% RBS:

$$D=0.144702564\frac{TS}{\lambda}\cdot\ln\left(0.001041026\frac{TS}{\lambda}\cdot Q\right)+3.02$$

$$D=1.39\ln(0.01\cdot Q)+3.02$$

For Remanent Strength=80% RBS:

$$D=0.144702564\frac{TS}{\lambda}\cdot\ln\left(0.001041026\frac{TS}{\lambda}\cdot Q\right)+2.94$$

$$D=1.39\ln(0.01\cdot Q)+2.94$$

For Remanent Strength=75% RBS:

$$D=0.144702564\frac{TS}{\lambda}\cdot\ln\left(0.001041026\frac{TS}{\lambda}\cdot Q\right)+2.86$$

$$D=1.39\ln(0.01\cdot Q)+2.86$$

Positive Polarity:

For Remanent Strength=90% RBS:

$$D=0.144702564\frac{TS}{\lambda}\cdot\ln\left(0.001041026\frac{TS}{\lambda}\cdot Q/2\right)+3.10$$

$$D=1.39\ln(0.01\cdot Q/2)+3.10$$

For Remanent Strength=85% RBS:

$$D=0.144702564\frac{TS}{\lambda}\cdot\ln\left(0.001041026\frac{TS}{\lambda}\cdot Q/2\right)+3.02$$

$$D=1.39\ln(0.01\cdot Q/2)+3.02$$

For Remanent Strength=80% RBS:

$$D=0.144702564\frac{TS}{\lambda}\cdot\ln\left(0.001041026\frac{TS}{\lambda}\cdot Q/2\right)+2.94$$

$$D=1.39\ln(0.01\cdot Q/2)+2.94$$

For Remanent Strength=75% RBS:

$$D=0.144702564\frac{TS}{\lambda}\cdot\ln\left(0.001041026\frac{TS}{\lambda}\cdot Q/2\right)+2.86$$

$$D=1.39\ln(0.01\cdot Q/2)+2.86$$

		4
1	90	
2	85	
3	80	
4	75	

APPENDIX

PLS-CADD Version 10.64x64   3:38:35 PM Friday, November 19, 2010
Power Engineers
Project Name: 'r:\pls\pls_cadd\projects\119990 clean line\clean line_span comparison_bluebird_1500 ft.LOA'

Criteria notes:
Clean Line Structure Load Trees
NESC Heavy Common Point
HS=VS=1500ft
0° Final After Load @25% Controls (Conductor)
0° Final After Creep @15% Controls OPGW

Section #6 '3:1:Ahead'
Cable 'r:\pls\pls_cadd\projects\119990 clean line\cables\bluebird_acsr.wir', Ruling span (ft) 1500
Sagging data: Catenary (ft) 5542.19, Horiz. Tension (lbs) 13916.4 Condition I Temperature (deg F) 60.0001
Note: Temperature and condition above are program supplied defaults used for automatic sagging.
Weather case for final after creep 60, Equivalent to 78.9 (deg F) temperature increase
Weather case for final after load NESC Heavy-Rule 250B, Equivalent to 24.1 (deg F) temperature increase

Ruling Span Sag Tension Report

Weather Case		Cable Load			R.S. Initial Cond.					R.S. Final Cond. After Creep					R.S. Final Cond. After Load				
#	Description	Hor. Load (lbs/ft)	Vert Load (lbs/ft)	Res. Load (lbs/ft)	Max. Tens. (lbs)	Hori. Tens. (lbs)	Max Ten %UL	C (ft)	R.S. Sag (ft)	Max. Tens. (lbs)	Hori. Tens. (lbs)	Max Ten %UL	C (ft)	R.S. Sag (ft)	Max. Tens. (lbs)	Hori. Tens. (lbs)	Max Ten %UL	C (ft)	R.S. Sag (ft)
1	NESC Heavy-Rule 250B	0.92	3.92	4.32	23767	23344	39	5399	52.18	22085	21630	37	5002	56.33	23767	23344	39	5399	52.18
2	NESC Rule 250D	1.46	7.19	7.34	34530	33551	57	4572	61.66	33973	32977	56	4494	62.74	34530	33551	57	4572	61.66
3	32deg, .5", 0psf	0.00	3.92	3.92	21258	20796	35	5309	53.07	19576	19074	32	4869	57.88	21010	20542	35	5244	53.73
4	60deg, 0", 97mph	3.57	2.51	4.36	22217	21874	37	5013	56.20	20618	20248	34	4641	60.74	22010	21664	37	4965	56.75
5	60deg, 0", 157mph	9.27	2.51	9.60	39677	38961	66	4059	69.49	39677	38961	66	4059	69.49	39677	38961	66	4059	69.49
6	60deg, 0", 12.2 psf	1.79	2.51	3.08	16823	16530	28	5359	52.57	15232	14907	25	4833	58.31	16367	16065	27	5208	54.09
7	0deg, 0", 4psf	0.59	2.51	2.58	15940	15681	26	6081	46.31	14117	13825	23	5361	52.55	15414	15147	26	5874	47.95
8	60deg, 0", 6psf	0.88	2.51	2.66	14901	14616	25	5493	51.28	13370	13051	22	4905	57.46	14402	14107	24	5301	53.14
9	0	0.00	2.51	2.51	15607	15349	26	6113	46.07	13795	13503	23	5378	52.39	15073	14806	25	5896	47.76
10	32	0.00	2.51	2.51	14815	14544	25	5792	48.63	13179	12872	22	5126	54.96	14295	14013	24	5580	50.47
11	60	0.00	2.51	2.51	14200	13916	24	5542	50.83	12700	12382	21	4931	57.15	13694	13399	23	5336	52.79
12	90	0.00	2.51	2.51	13605	13309	23	5300	53.15	12236	11905	20	4741	59.45	13126	12819	22	5105	55.19
13	120	0.00	2.51	2.51	13076	12767	22	5084	55.42	11817	11474	20	4570	61.69	12621	12300	21	4899	57.53
14	148	0.00	2.51	2.51	12625	12305	21	4900	57.51	11461	11107	19	4423	63.73	12194	11862	20	4724	59.66
15	160	0.00	2.51	2.51	12446	12121	21	4827	58.38	11319	10960	19	4365	64.59	12024	11688	20	4655	60.55
16	284	0.00	2.51	2.51	10929	10558	18	4205	67.07	10110	9707	17	3866	72.98	10598	10214	18	4068	69.34

PLS-CADD Version 10.60 11:52:49 AM Tuesday, October 05, 2010
Power Engineers
Project Name: 'r:\pls\pls_cadd\projects\119990 clean line\clean line str. analysis_bluebird_sag.LOA'

Criteria notes:
Clean Line Structure Load Trees
NESC Heavy Common Point
HS=VS=1500ft
0° Final After Load @25% Controls (Cond.)
0° Final After Creep @15% Controls (opgw)

Section #1 '1:1:Back'
Cable 'r:\pls\pls_cadd\projects\119990 clean line\cables\49ay85acs-2c 1-1427.wir', Ruling span (ft) 1500
Sagging data: Catenary (ft) 7672.59, Horiz. Tension (lbs) 3629.14 Condition I Temperature (deg F) 60.0001
Note: Temperature and condition above are program supplied defaults used for automatic sagging.
Weather case for final after creep 60, Equivalent to 37.8 (deg F) temperature increase
Weather case for final after load NESC Heavy-Rule 250B, Equivalent to 46.6 (deg F) temperature increase

Ruling Span Sag Tension Report

Weather Case		Cable Load (lbs/ft)			R.S. Initial Cond.					R.S. Final Cond. After Creep					R.S. Final Cond. After Load				
#	Description	Hor.	Vert	Res.	Max. Tens. (lbs)	Hori. Tens. (lbs)	Max Ten %UL	C (ft)	R.S. Sag (ft)	Max. Tens. (lbs)	Hori. Tens. (lbs)	Max Ten %UL	C (ft)	R.S. Sag (ft)	Max. Tens. (lbs)	Hori. Tens. (lbs)	Max Ten %UL	C (ft)	R.S. Sag (ft)
1	NESC Heavy-Rule 250B	0.53	1.15	1.57	8826	8774	35	5597	50.32	8826	8774	35	5597	50.32	8826	8774	35	5597	50.32
2	NESC Rule 250D	1.06	3.33	3.50	14652	14415	58	4121	68.44	14652	14415	58	4121	68.44	14652	14415	58	4121	68.44
3	32deg, .5", 0psf	0.00	1.15	1.15	7020	6967	28	6051	46.54	6935	6881	27	5977	47.12	6871	6817	27	5921	47.57
4	60deg, 0", 97mph	1.20	0.47	1.29	7366	7302	29	5674	49.64	7310	7246	29	5631	50.02	7248	7184	29	5582	50.46
5	60deg, 0", 12.2 psf	0.60	0.47	0.76	5133	5101	20	6671	42.21	4946	4912	19	6424	43.83	4889	4856	19	6350	44.34
6	0deg, 0", 4psf	0.20	0.47	0.51	4305	4288	17	8368	33.63	4032	4014	16	7833	35.93	3969	3950	16	7710	36.51
7	60deg, 0", 6psf	0.30	0.47	0.56	4105	4083	16	7322	38.45	3878	3855	15	6913	40.73	3826	3803	15	6819	41.29
8	0	0.00	0.47	0.47	4089	4074	16	8613	32.67	3804	3788	15	8008	35.15	3743	3726	15	7877	35.73
9	32	0.00	0.47	0.47	3839	3823	15	8082	34.82	3581	3563	14	7533	37.36	3526	3508	14	7417	37.95
10	60	0.00	0.47	0.47	3646	3629	14	7673	36.69	3408	3389	13	7165	39.29	3358	3339	13	7060	39.88
11	90	0.00	0.47	0.47	3460	3442	14	7277	38.68	3243	3224	13	6816	41.31	3199	3179	13	6722	41.89
12	120	0.00	0.47	0.47	3295	3276	13	6926	40.65	3096	3076	12	6503	43.30	3057	3037	12	6420	43.86
13	284	0.00	0.47	0.47	2646	2622	10	5544	50.81	2522	2497	10	5278	53.38	2499	2474	10	5231	53.86

PLS-CADD Version 10.64x64   3:03:14 PM Friday, December 10, 2010
Power Engineers
Project Name: 'r:\pls\pls_cadd\projects\119990 clean line\clean line_river crossing=4000 ft-accr_tw cumberland.LOA'

Criteria notes:
River Crossing Span=4000 ft
0 deg F Final @25% Controls (Conductor ACCR/TW Cumberland)

Section #1 '1:Back'
Cable 'r:\pls\pls_cadd\projects\119990 clean line\cables\cumberland_accr_tw_dc.wir', Ruling span (ft) 4000
Sagging data: Catenary (ft) 7437.05, Horiz. Tension (lbs) 15655 Condition I Temperature (deg F) 60.0001
Weather case for final after creep 60, Equivalent to 47.3 (deg F) temperature increase
Weather case for final after load NESC Heavy-Rule 250B, Equivalent to 40.3 (deg F) temperature increase

Ruling Span Sag Tension Report

Weather Case		Cable Load (lbs/ft)			R.S. Initial Cond.					R.S. Final Cond. After Creep					R.S. Final Cond. After Load					
#	Description	Hor. Load	Vert Load	Res. Load	Max. Tens. (lbs)	Hori. Tens. (lbs)	Max Ten %UL	C (ft)	R.S. Sag (ft)	Max. Tens. (lbs)	Hori. Tens. (lbs)	Max Ten %UL	C (ft)	R.S. Sag (ft)	Max. Tens. (lbs)	Hori. Tens. (lbs)	Max Ten %UL	C (ft)	R.S. Sag (ft)	
1	NESC Heavy-Rule 250B	0.85	3.38	3.78	28649	27607	44	7303	275.57	28579	27534	44	7284	276.30	28649	27607	44	7303	275.57	
2	NESC Rule 250D	1.38	6.45	6.59	47068	45128	72	6845	294.27	47068	45128	72	6845	294.27	47068	45128	72	6845	294.27	
3	32deg, .5", 0psf	0.00	3.38	3.38	25568	24637	39	7299	275.72	25386	24448	39	7243	277.88	25447	24511	39	7262	277.15	
4	60deg, 0", 97mph	3.12	2.11	3.77	28106	27049	43	7180	280.37	27929	26865	43	7131	282.31	27995	26935	43	7149	281.58	
5	60deg, 0", 12.2 psf	1.57	2.11	2.63	20025	19307	31	7354	273.63	19759	19030	30	7249	277.66	19807	19080	30	7268	276.92	
6	0deg, 0", 4psf	0.51	2.11	2.17	16991	16415	26	7575	265.55	16764	16180	26	7467	269.46	16805	16223	26	7487	268.74	
7	60deg, 0", 6psf	0.77	2.11	2.24	17232	16624	26	7415	271.36	16964	16345	26	7291	276.05	17004	16387	26	7309	275.33	
8	0	0.00	2.11	2.11	16528	15970	25	7587	265.15	16300	15733	25	7474	269.19	16341	15776	25	7494	268.45	
9	32	0.00	2.11	2.11	16365	15801	25	7506	268.03	16114	15541	25	7383	272.56	16156	15583	25	7403	271.81	
10	60	0.00	2.11	2.11	16224	15654	25	7437	270.56	15958	15379	24	7306	275.47	15998	15419	24	7325	274.73	
11	90	0.00	2.11	2.11	16077	15502	25	7364	273.25	15795	15208	24	7225	278.59	15832	15247	24	7243	277.88	
12	120	0.00	2.11	2.11	15933	15352	24	7293	275.95	15637	15044	24	7147	281.67	15676	15084	24	7166	280.92	
13	152	0.00	2.11	2.11	15783	15196	24	7219	278.82	15474	14874	24	7066	284.93	15509	14911	24	7084	284.22	MOT-Normal
14	166	0.00	2.11	2.11	15718	15128	24	7187	280.09	15403	14800	24	7031	286.39	15438	14837	24	7048	285.67	MOT-Emergency

PLS-CADD Version 10.64x64   8:42:50 AM Wednesday, December 15, 2010
Power Engineers
Project Name: 'r:\pls\pls_cadd\projects\119990 clean line\clean line_river crossing=4000 ft-opgw 161acs-2c.loa'

Criteria notes:
River Crossing Span=4000 ft
NESC -Rule 250D- Extreme ice with Concurrent Wind-Initial @75% Controls (OPGW)

Section #1 '1:Back'
Cable 'r:\pls\pls_cadd\projects\119990 clean line\cables\mississippi river crossing-conductor selection\brugg_161acs-2c 1-1140.wir', Ruling span (ft) 4000
Sagging data: Catenary (ft) 9262.54, Horiz. Tension (lbs) 6280 Condition I Temperature (deg F) 60.0001
Weather case for final after creep 60, Equivalent to 47.3 (deg F) temperature increase
Weather case for final after load NESC Heavy-Rule 250B, Equivalent to 26.5 (deg F) temperature increase

Ruling Span Sag Tension Report

Weather Case		Cable Load (lbs/ft)			R.S. Initial Cond.					R.S. Final Cond. After Creep					R.S. Final Cond. After Load					
#	Description	Hor. Load	Vert Load	Res. Load	Max. Tens. (lbs)	Hori. Tens. (lbs)	Max Ten %UL	C (ft)	R.S. Sag (ft)	Max. Tens. (lbs)	Hori. Tens. (lbs)	Max Ten %UL	C (ft)	R.S. Sag (ft)	Max. Tens. (lbs)	Hori. Tens. (lbs)	Max Ten %UL	C (ft)	R.S. Sag (ft)	
1	NESC Heavy-Rule 250B	0.55	1.39	1.79	15580	15153	41	8442	238.01	15480	15050	41	8385	239.66	15580	15153	41	8442	238.01	
2	NESC Rule 250D	1.07	3.63	3.78	28550	27504	75	7274	276.70	28550	27504	75	7274	276.70	28550	27504	75	7274	276.70	
3	32deg, .5", 0psf	0.00	1.39	1.39	12384	12062	33	8674	231.59	12248	11922	32	8574	234.34	12333	12010	32	8637	232.61	
4	60deg, 0", 97mph	1.31	0.68	1.47	12905	12558	34	8523	235.74	12775	12424	34	8432	238.31	12860	12511	34	8492	236.62	
5	60deg, 0", 12.2 psf	0.66	0.68	0.94	8694	8483	23	8987	223.47	8556	8341	22	8837	227.29	8621	8409	23	8908	225.46	
6	0deg, 0", 4psf	0.22	0.68	0.71	6887	6736	18	9469	211.99	6754	6600	18	9278	216.41	6812	6659	18	9361	214.46	
7	60deg, 0", 6psf	0.32	0.68	0.75	7062	6897	19	9184	218.63	6934	6766	18	9010	222.90	6990	6824	18	9086	221.01	
8	0	0.00	0.68	0.68	6591	6448	17	9510	211.08	6460	6314	17	9313	215.59	6516	6371	17	9397	213.63	
9	32	0.00	0.68	0.68	6502	6357	17	9376	214.13	6376	6228	17	9186	218.59	6430	6283	17	9268	216.64	
10	60	0.00	0.68	0.68	6427	6280	17	9262	216.77	6305	6155	17	9078	221.20	6357	6209	17	9157	219.27	
11	90	0.00	0.68	0.68	6350	6201	17	9146	219.55	6232	6080	16	8968	223.95	6282	6132	16	9044	222.05	
12	120	0.00	0.68	0.68	6275	6125	16	9033	222.31	6161	6007	16	8860	226.70	6209	6057	16	8933	224.83	MOT-OPGW
13	152	0.00	0.68	0.68	6198	6045	16	8916	225.26	6088	5932	16	8749	229.59	6135	5980	16	8820	227.72	MOT-Normal-Conductor
14	166	0.00	0.68	0.68	6165	6012	16	8867	226.52	6056	5900	16	8702	230.85	6102	5947	16	8772	229.00	MOT-Emergency-Conductor

(OPGW Sag @ 60 F, No Ice , No Wind, Final)/(Conductor ACCR/TW Cumberland Sag @ 60 F, No Ice, No Wind, Final)x100= 221.20/275.47x100=80.3% <=85%, OK

(OPGW Sag @ 32 F, 0.5" Ice, No Wind, Final)/(Conductor ACCR/TW Cumberland Sag @ 32 F, No Ice, No Wind, Final)x100= 234.34/272.56x100=85.9% <=95%, OK

APPENDIX

PLS-CADD Version 10.64x64   3:16:39 PM Friday, November 19, 2010
Power Engineers
Project Name: 'r:\pls\pls_cadd\projects\119990 clean line\clean line_plains & eastern 600kv dc_segment 3.DON'

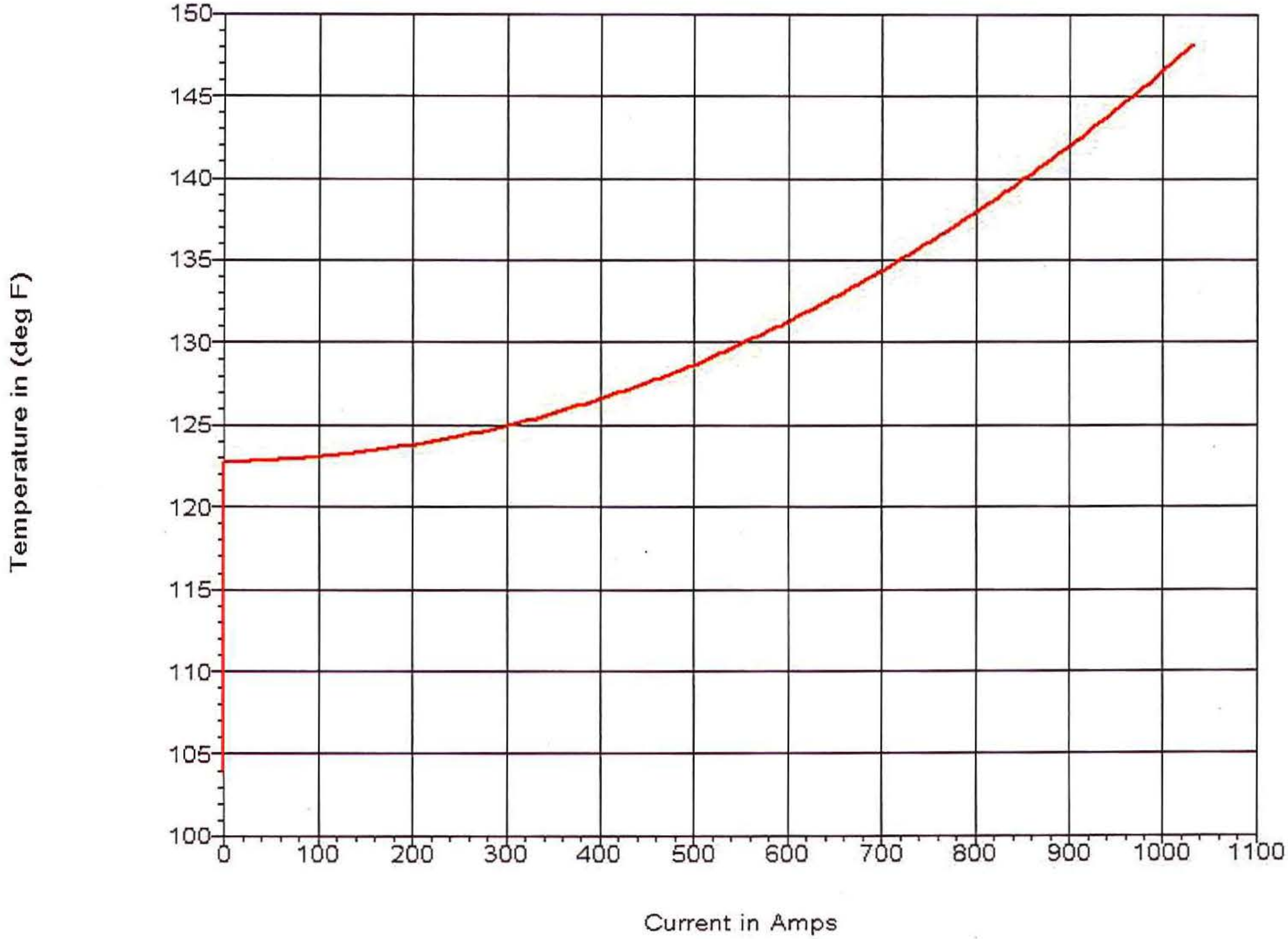
IEEE Std. 738-2006 method of calculation
NRMAL REGIME: I pole=3100 A; I conductor=I pole/3=1033.3 A

Air temperature is 104.00 (deg F)=40 (deg C)
Wind speed is 2.00 (ft/s)
Angle between wind and conductor is 90 (deg)
Conductor elevation above sea level is 1000 (ft)
Conductor bearing is -16 (deg) (perpendicular to solar azimuth for maximum solar heating)
Sun time is 14 hours (solar altitude is 62 deg. and solar azimuth is -106 deg.)
Conductor latitude is 35.0 (deg)
Atmosphere is CLEAR
Day of year is 172 (corresponds to June 21 in year 2010) (day of the year with most solar heating)

Conductor description: 2156 kcmil 84/19 Strands BLUEBIRD ACSR - Adapted from 1970's Publicly Available Data
Conductor diameter is 1.762 (in)
Conductor resistance is 0.0423 (Ohm/mile) at 68.0 (deg F)
and 0.0499 (Ohm/mile) at 167.0 (deg F)
Emissivity is 0.5 and solar absorptivity is 0.5

Solar heat input is 7.088 (Watt/ft) (corresponds to Global Solar Radiation of 96.549 (Watt/ft^2) - which was calculated)
Radiation cooling is 4.120 (Watt/ft)
Convective cooling is 12.764 (Watt/ft)

Given a constant ac current of 1033.3 amperes,
The conductor temperature is 148.2 (deg F)=64 (deg C)



150
145
140
135
130
125
120
115
110
105
100
Temperature in (deg F)
0
100
200
300
400
500
600
700
800
900
1000
1100
Current in Amps

PLS-CADD Version 10.64x64   2:58:27 PM Friday, November 19, 2010
Power Engineers
Project Name: 'r:\pls\pls_cadd\projects\119990 clean line\clean line_plains & eastern 600kv dc_segment 3.DON'

IEEE Std. 738-2006 method of calculation

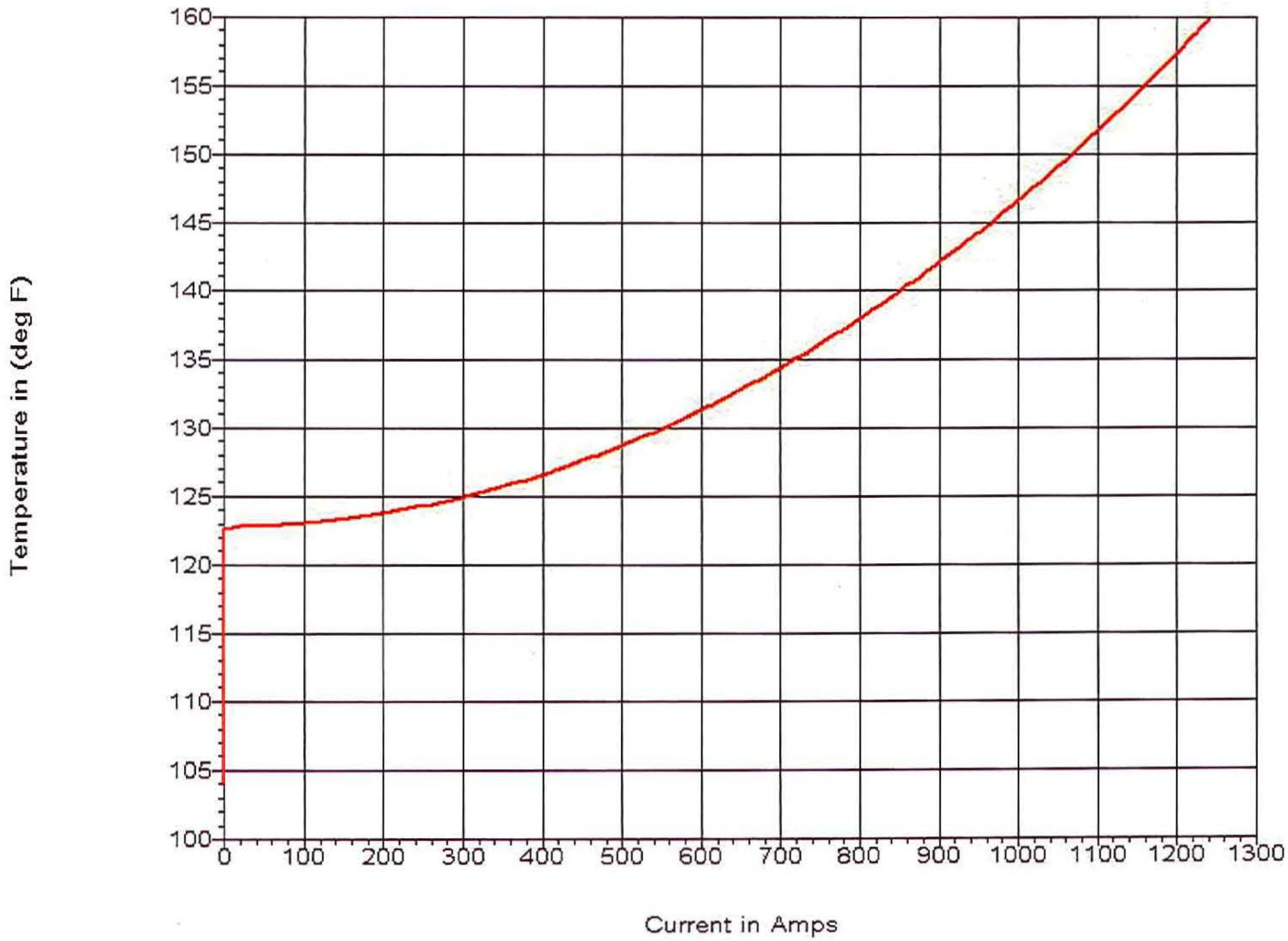
EMERGENCY REGIME: I pole=3720 A; I conductor=I pole/3=1240 A
(20% over Normal Regime: I pole=3100 A; I conductor=I pole/3=1033.3 A)

Air temperature is 104.00 (deg F)
Wind speed is 2.00 (ft/s)
Angle between wind and conductor is 90 (deg)
Conductor elevation above sea level is 1000 (ft)
Conductor bearing is -16 (deg) (perpendicular to solar azimuth for maximum solar heating)
Sun time is 14 hours (solar altitude is 62 deg. and solar azimuth is -106 deg.)
Conductor latitude is 35.0 (deg)
Atmosphere is CLEAR
Day of year is 172 (corresponds to June 21 in year 2010) (day of the year with most solar heating)

Conductor description: 2156 kcmil 84/19 Strands BLUEBIRD ACSR - Adapted from 1970's Publicly Available Data
Conductor diameter is 1.762 (in)
Conductor resistance is 0.0423 (Ohm/mile) at 68.0 (deg F)
and 0.0499 (Ohm/mile) at 167.0 (deg F)
Emissivity is 0.5 and solar absorptivity is 0.5

Solar heat input is 7.088 (Watt/ft) (corresponds to Global Solar Radiation of 96.549 (Watt/ft^2) - which was calculated)
Radiation cooling is 5.359 (Watt/ft)
Convective cooling is 16.099 (Watt/ft)

Given a constant ac current of 1240.0 amperes,
The conductor temperature is 159.8 (deg F)=71 (deg C)



160
155
150
145
140
135
130
125
120
115
110
105
100
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
Temperature in (deg F)
Current in Amps

Project Name: 'r:\pls\pls_cadd\projects\119990 clean line\clean line_plains & eastern 600kv dc_segment 7.DON'

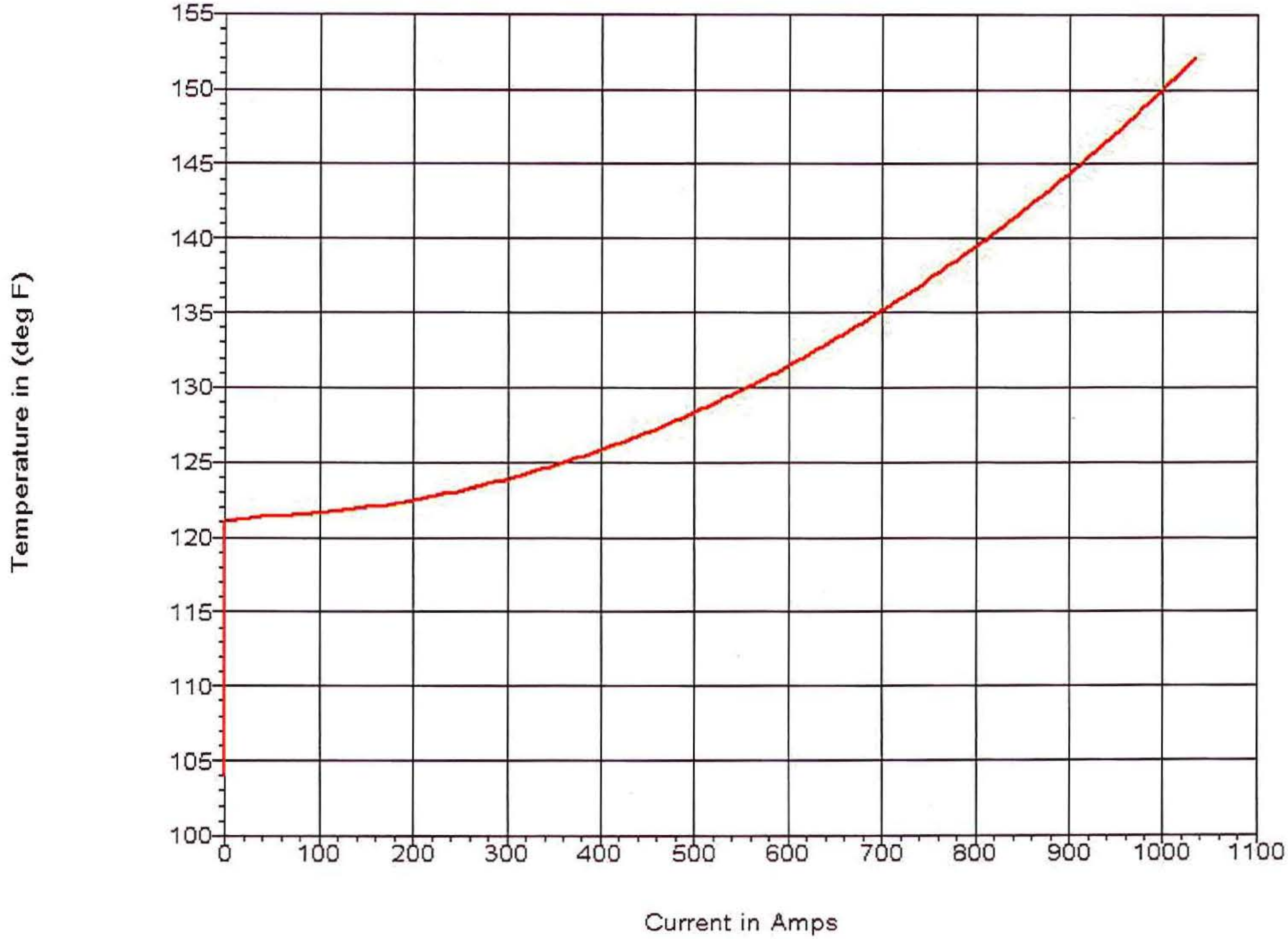
IEEE Std. 738-2006 method of calculation
NORMAL REGIME: I pole=3100 A; I conductor=I pole/3=1033.3 A

Air temperature is 104.00 (deg F)=40 (deg C)
Wind speed is 2.00 (ft/s)
Angle between wind and conductor is 90 (deg)
Conductor elevation above sea level is 300 (ft)-at Mississippi River Crossing Span=4000 ft.
Conductor bearing is -16 (deg) (perpendicular to solar azimuth for maximum solar heating)
Sun time is 14 hours (solar altitude is 62 deg. and solar azimuth is -106 deg.)
Conductor latitude is 35.0 (deg)
Atmosphere is CLEAR
Day of year is 172 (corresponds to June 21 in year 2010) (day of the year with most solar heating)

Conductor description: ACCR-TW_1927-T13 Cumberland
Conductor diameter is 1.543 (in)
Conductor resistance is 0.0461 (Ohm/mile) at 68.0 (deg F)
and 0.0560 (Ohm/mile) at 167.0 (deg F)
Emissivity is 0.5 and solar absorptivity is 0.5

Solar heat input is 6.066 (Watt/ft) (corresponds to Global Solar Radiation of 94.350 (Watt/ft^2) - which was calculated)
Radiation cooling is 3.961 (Watt/ft)
Convective cooling is 13.129 (Watt/ft)

Given a constant dc current of 1033.3 amperes,
The conductor temperature is 152.1 (deg F)=67 (deg C)



155
150
145
140
135
130
125
120
115
110
105
100
Temperature in (deg F)
0
100
200
300
400
500
600
700
800
900
1000
1100
Current in Amps

Project Name: 'r:\pls\pls_cadd\projects\119990 clean line\clean line_plains & eastern 600kv dc_segment 7.DON'

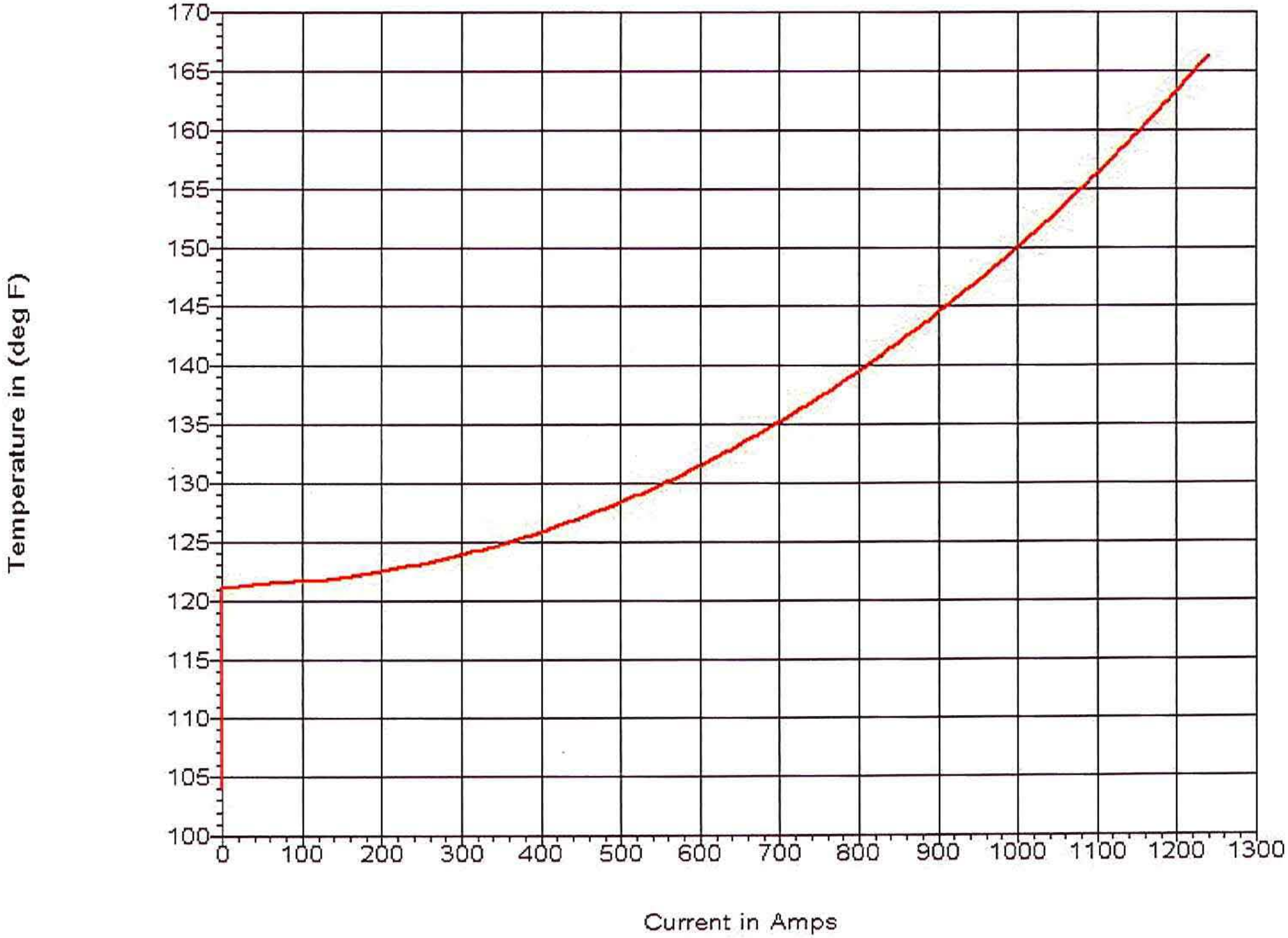
IEEE Std. 738-2006 method of calculation
EMERGENCY REGIME: I pole=3720 A; I conductor=I pole/3=1240 A
(20% over Normal Regime: I pole=3100 A; I condcutor=I pole/3=1033.3 A)

Air temperature is 104.00 (deg F)=40 (deg C)
Wind speed is 2.00 (ft/s)
Angle between wind and conductor is 90 (deg)
Conductor elevation above sea level is 300 (ft)
Conductor bearing is -16 (deg) (perpendicular to solar azimuth for maximum solar heating)
Sun time is 14 hours (solar altitude is 62 deg. and solar azimuth is -106 deg.)
Conductor latitude is 35.0 (deg)
Atmosphere is CLEAR
Day of year is 172 (corresponds to June 21 in year 2010) (day of the year with most solar heating)

Conductor description: ACCR-TW_1927-T13 Cumberland
Conductor diameter is 1.543 (in)
Conductor resistance is 0.0461 (Ohm/mile) at 68.0 (deg F)
and 0.0560 (Ohm/mile) at 167.0 (deg F)
Emissivity is 0.5 and solar absorptivity is 0.5

Solar heat input is 6.066 (Watt/ft) (corresponds to Global Solar Radiation of 94.350 (Watt/ft^2) - which was calculated)
Radiation cooling is 5.333 (Watt/ft)
Convective cooling is 17.021 (Watt/ft)

Given a constant dc current of 1240.0 amperes,
The conductor temperature is 166.4 (deg F)=74 (deg C)

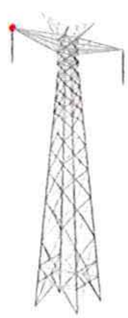

170
165
160
155
150
145
140
135
130
125
120
115
110
105
100
Temperature in (deg F)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
Current in Amps

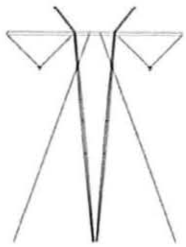
APPENDIX

600 kV DC Line –Clean Line Project # 119990

Horizontal Bipolar Line

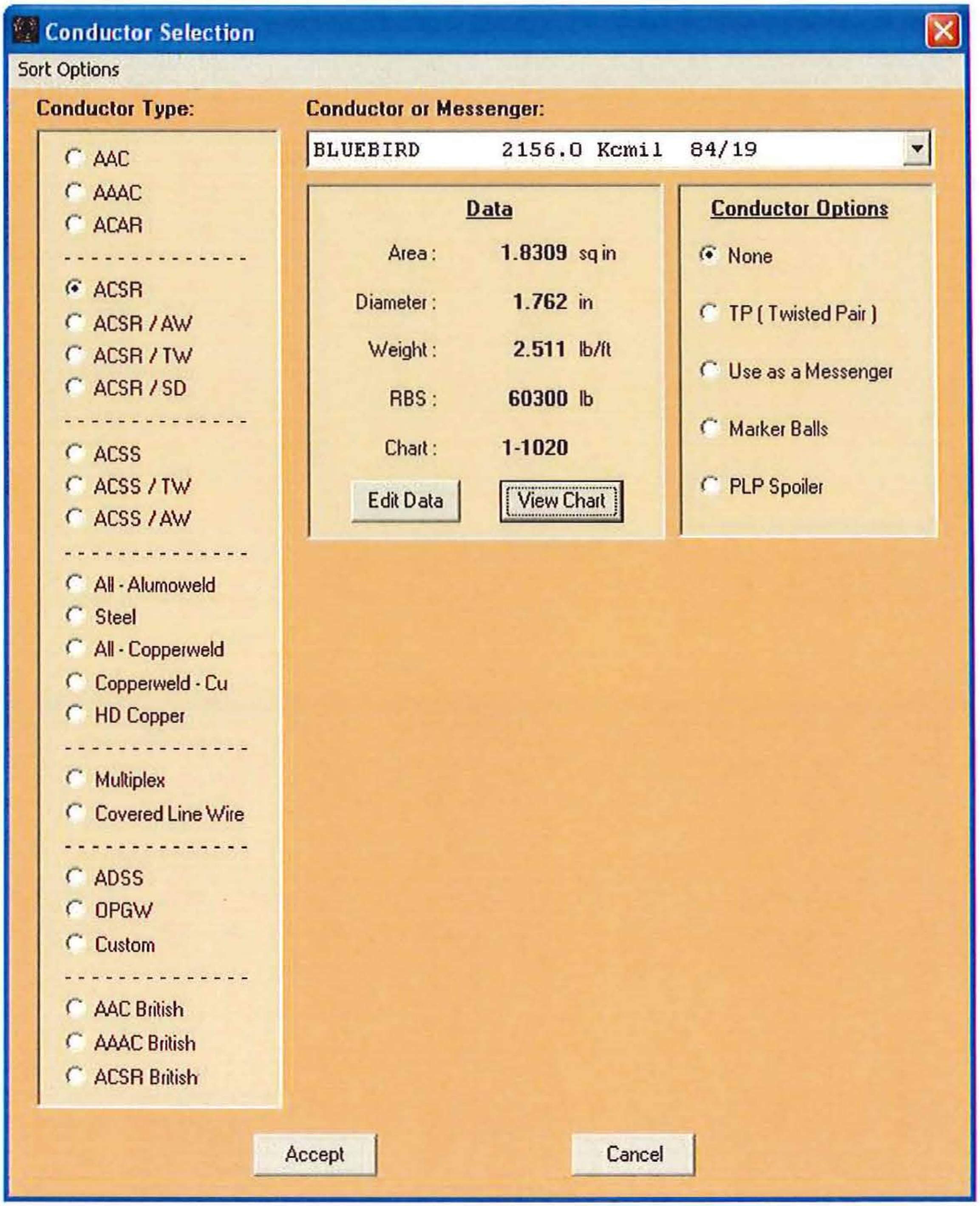
Comparison of Structure Types

Structure Type	Drawing	Advantages	Disadvantages	Conclusion
Self-Supported Steel Single Tubular		• reduced land use • line compaction • smaller footprint than any of the guyed types • shorter lead time vs. steel lattice • shorter construction time vs. steel lattice. • Needs less design time than steel lattice. • Does not use so many plates, gussets, fasteners and bolts as steel lattice • Does not need galvanizing as much as the steel lattice.	• cover shorter spans than steel lattice for same external extreme loading cases. • expensive foundation.	• Good for urban & sub-urban areas (farming land with irrigation) on the corridor of this Clean Line HVDC project. • Good for areas with restricted and/or reduced ROW • Not used too much in open country ROW, unless farm land with irrigation or special environment requirements.
Self-Supporting Steel Lattice		• Suitable for rugged terrain (mountains, valleys, river crossings, etc) • Smaller footprint than any of the guyed types. • Past experience with HVDC lines in USA and internationally, with very good reliability. • Use of different extension legs and extension bodies, makes it suitable for worst rough terrain.	• Requires 4 foundations (higher total foundation costs). • Highest weight (heaviest of all types). • Long lead times • Longer construction time • Needs more design time. • More exposed wind area (higher forces on structure). • Heavier equipment used during erection vs. CSR type.	• Best solution for rugged terrain (mountains) on the corridor of this Clean Line HVDC project, with very good reliability proved in many years of field presence, even for HVDC lines.

Guyed Mast Variant 1: Tubular Steel V-String Variant 2: Lattice Steel I-String	 	• Single foundation. • Very light. • In the tubular steel variant, less material than in the self-supported lattice steel (less expensive), for same height. • Some past experience with HVDC lines in USA and internationally.	• Difficult to use in the ROW of mountain zones • The 4 anchored guys take a lot of space from the ROW. • Possible rotational effect in case of slack guy or any minor anchor movement (it can be eliminated by attaching the guys with brackets to the front and back of the tower, instead of being attached to the tower on the opposite side of each anchor).	• A far less expensive solution for the open country zones of the corridor of this Clean Line HVDC project, as long as it does not have irrigation system.
Cross-Rope Suspension (CSR) with2 Masts Variant 1: Portal Formation 2 Foundations I-String Variant 2: V-Formation 1 Foundation V-String	 	• The most economical. • Lowest weight, for same height, from all types of structures. • High strength/weight ratio • Lower cost of erection. • Flexible suspension catenary (anti-cascading structure). • Claimed that it can sustain the loss of 1 guy w/o collapsing. • In the portal type, the masts can have different lengths, for use in irregular terrain. • Light equipment used during erection. • The strength of the tower can be increased by using larger or stronger steel	• Difficult to assembly in the ROW of mountain zones. • Very large base makes it incompatible with large irrigation systems. • Lack of previous experience with CSR tower in USA makes it difficult to obtain permit. • Small footing print, but it takes a lot from the ROW due to its large base. • It can collapse, if guys are lost. • The portal type requires a larger space than the guyed single mast type. • Maintenance Safety: access to the insulator string and conductor supports it is a concern to line field personnel.	• Due to its very large base that makes it incompatible with large irrigation systems and due to lack of previous experience with CSR tower in USA, making it difficult to obtain permit, plus the safety concern (access to insulator and conductors during maintenance work), the CSR type is not recommend to be used on this Clean Line HVDC project.

		cables. • Used extensively in international HVAC lines 400 kV- 800 KV (Brazil, Argentina, South Africa, Canada).		

APPENDIX H



Conductor Selection
Sort Options
Conductor Type:
AAC
AAAC
ACAR
ACSR
ACSR / AW
ACSR / TW
ACSR / SD
ACSS
ACSS / TW
ACSS / AW
All - Alumoweld
Steel
All - Copperweld
Copperweld - Cu
HD Copper
Multiplex
Covered Line Wire
ADSS
OPGW
Custom
AAC British
AAAC British
ACSR British
Conductor or Messenger:
BLUEBIRD 2156.0 Kcmil 84/19
Data
Area : 1.8309 sq in
Diameter : 1.762 in
Weight : 2.511 lb/ft
RBS : 60300 lb
Chart : 1-1020
Edit Data
View Chart
Conductor Options
None
TP (Twisted Pair)
Use as a Messenger
Marker Balls
PLP Spoiler
Accept
Cancel

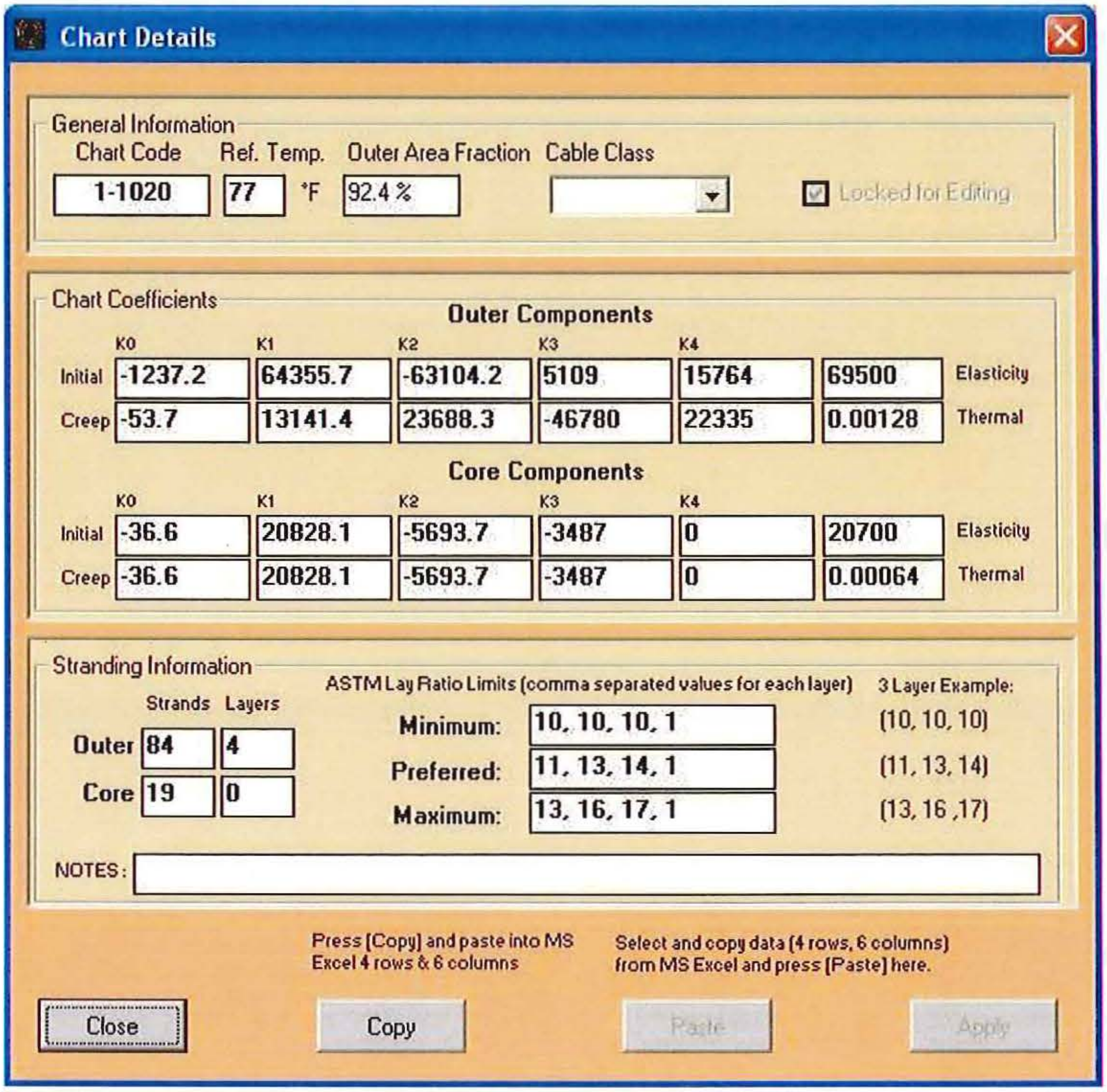


Chart Details
General Information
Chart Code
Ref. Temp.
Outer Area Fraction
Cable Class
1-1020
77
°F
92.4 %
Locked for Editing
Chart Coefficients
Outer Components
K0
K1
K2
K3
K4
Initial
-1237.2
64355.7
-63104.2
5109
15764
69500
Elasticity
Creep
-53.7
13141.4
23688.3
-46780
22335
0.00128
Thermal
Core Components
K0
K1
K2
K3
K4
Initial
-36.6
20828.1
-5693.7
-3487
0
20700
Elasticity
Creep
-36.6
20828.1
-5693.7
-3487
0
0.00064
Thermal
Stranding Information
Strands
Layers
Outer
84
4
Core
19
0
ASTM Lay Ratio Limits (comma separated values for each layer)
Minimum:
10, 10, 10, 1
Preferred:
11, 13, 14, 1
Maximum:
13, 16, 17, 1
3 Layer Example:
(10, 10, 10)
(11, 13, 14)
(13, 16 ,17)
NOTES:
Press [Copy] and paste into MS Excel 4 rows & 6 columns
Select and copy data (4 rows, 6 columns) from MS Excel and press [Paste] here.
Close
Copy
Paste
Apply

acsr_bluebird_dc.wir: the resistances values in this table are DC Resistances:

Cable Data

Cable Model

- (•) Nonlinear cable model (separate polynomials for initial and creep behavior for inner and outer materials)
- ( ) Linear elastic with permanent stretch due to creep proportional to creep weather case tension
- ( ) Linear elastic with permanent stretch due to creep specified as a user input temperature increase

Name: r:\pls\pls_cadd\projects\119990 clean line\cables\bluebird_acsr_dc.wir

Description: 2156 kcmil 84/19 Strands BLUEBIRD ACSR - Adapted from 1970's Publicly Available Data

Stock Number:

Cross section area (in^2) 1.8309 | Unit weight (lbs/ft) 2.511 | Number of independent wires (1 unless messenger supporting other wires with a spacer) 1

Outside diameter (in) 1.762 | Ultimate tension (lbs) 60300

[ ] Conductor is a J-Power Systems GAP type conductor strung with core supporting all tension.

Temperature at which strand data below obtained (deg F) 77

Outer Strands

Final modulus of elasticity (see note below) (psi/100) 69500

Thermal expansion coeff. (/100 deg) 0.00128

Polynomial coefficients (all strains in %, stresses in psi, see note

	a0	a1	a2	a3	a4
Stress-strain	-1237.2	64355.7	-63104.	5109	15764
	c0	c1	c2	c3	c4
Creep	-53.7	13141.4	23688.3	-46780	22335

Note: Final modulus, stress-strain and creep are actual material values multiplied by ratio of outer strand area to total area.

Core Strands (if different from outer strands)

Final modulus of elasticity (see note below) (psi/100) 20700

Thermal expansion coeff. (/100 deg) 0.00064

Polynomial coefficients (all strains in %, stresses in psi, see note

	b0	b1	b2	b3	b4
Stress-strain	-36.6	20828.1	-5693.7	-3487	
	d0	d1	d2	d3	d4
Creep	-36.6	20828.1	-5693.7	-3487	

Note: Final modulus, stress-strain and creep are actual material values multiplied by ratio of core strand area to total area.

Bimetallic Conductor Model...

Aluminum has a larger thermal expansion coefficient than steel. If Aluminum is used as the outer material over a steel core there is a temperature transition point at which the aluminum is no longer under tension.

Select the behavior you want for temperatures above the transition point

- ( ) Use behavior from Criteria/Bimetallic Conductor Model
- ( ) Aluminum does not take compression at high temperature (Bird Cage)
- (•) Aluminum can go into compression at high temperature

VirtualStress = ActualStress * Ao / At
Ao = cross section area of outer strands
At = total cross section area of entire conductor (outer + inner strands)

Maximum virtual compressive stress (ksi) 1.5

Thermal Rating Properties

Resistance at two different temperatures

Resistance (Ohm/mile) 0.0423 at (deg F) 68

Resistance (Ohm/mile) 0.0499 at (deg F) 167

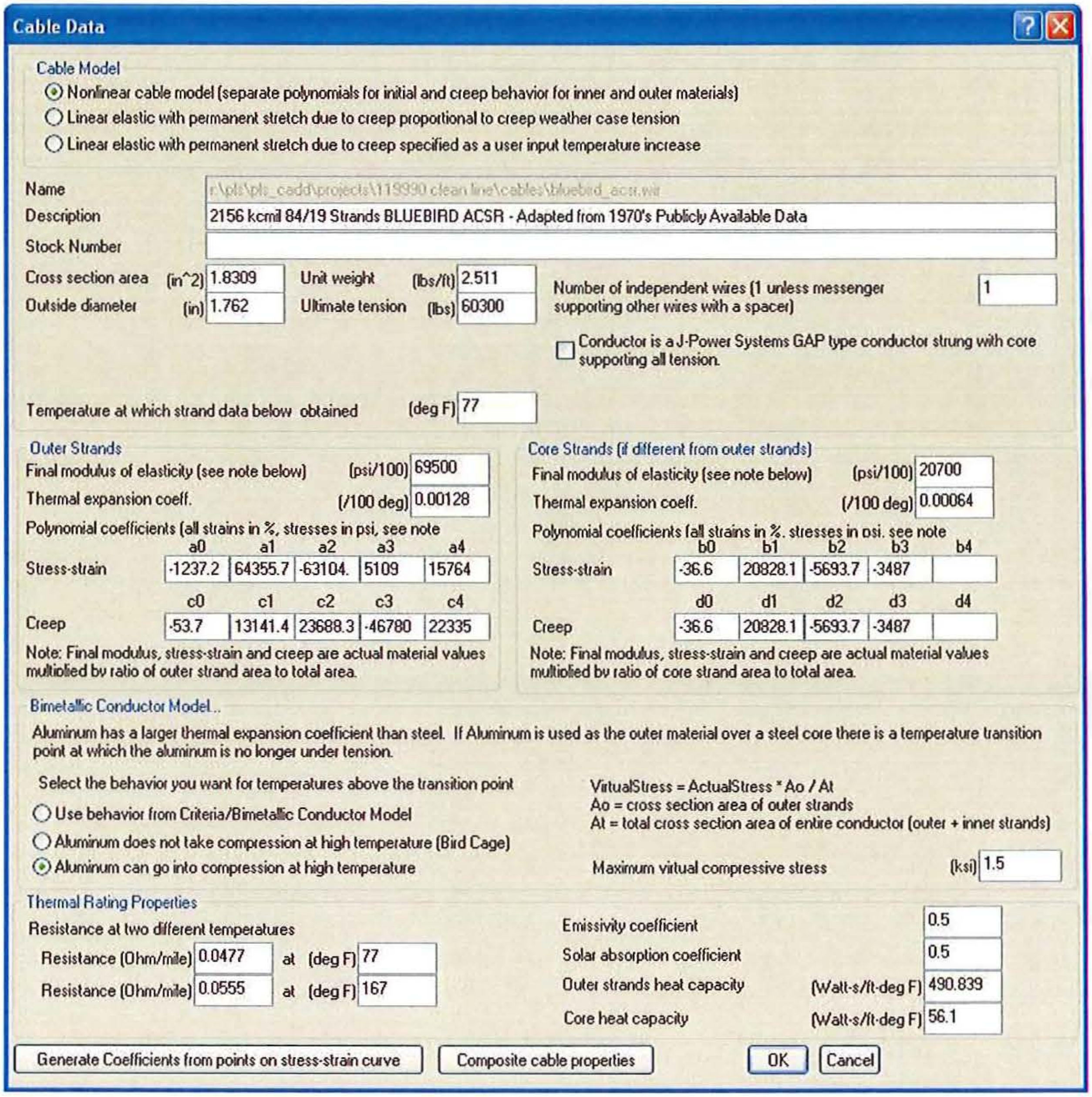
Emissivity coefficient 0.5

Solar absorption coefficient 0.5

Outer strands heat capacity (Watt-s/ft-deg F) 490.839

Core heat capacity (Watt-s/ft-deg F) 56.1

[Generate Coefficients from points on stress-strain curve] [Composite cable properties] [OK] [Cancel] acsr_bluebird.wir: the resistances values in this table are AC Resistances:



ACCR/TW Cumberland- with DC Resistances:

Cable Data

Cable Model

- (•) Nonlinear cable model (separate polynomials for initial and creep behavior for inner and outer materials)
- ( ) Linear elastic with permanent stretch due to creep proportional to creep weather case tension
- ( ) Linear elastic with permanent stretch due to creep specified as a user input temperature increase

Name: r:\pls\pls_cadd\projects\119390 clean line\cables\cumberland_accr_tw_dc.wir

Description: ACCR-TW_1927-T13

Stock Number:

Cross section area (in^2)	1.706	Unit weight (lbs/ft)	2.105
Outside diameter (in)	1.543	Ultimate tension (lbs)	65400

Number of independent wires (1 unless messenger supporting other wires with a spacer): 1

[ ] Conductor is a J-Power Systems GAP type conductor strung with core supporting all tension.

Temperature at which strand data below obtained (deg F): 71

Outer Strands

Final modulus of elasticity (see note below) (psi/100): 73240

Thermal expansion coeff. (/100 deg): 0.00128

Polynomial coefficients (all strains in %, stresses in psi, see note

	a0	a1	a2	a3	a4
Stress-strain		48031	-26987	-10552	5471
	c0	**c1**	**c2**	**c3**	**c4**
Creep		22914	-16099	4107	-2140

Note: Final modulus, stress-strain and creep are actual material values multiplied by ratio of outer strand area to total area.

Core Strands (if different from outer strands)

Final modulus of elasticity (see note below) (psi/100): 39816

Thermal expansion coeff. (/100 deg): 0.00035

Polynomial coefficients (all strains in %, stresses in psi, see note

	b0	b1	b2	b3	b4
Stress-strain		41889	-8641	-4105	2139
	d0	**d1**	**d2**	**d3**	**d4**
Creep		41889	-8641	-4105	2139

Note: Final modulus, stress-strain and creep are actual material values multiplied by ratio of core strand area to total area.

Bimetallic Conductor Model...

Aluminum has a larger thermal expansion coefficient than steel. If Aluminum is used as the outer material over a steel core there is a temperature transition point at which the aluminum is no longer under tension.

Select the behavior you want for temperatures above the transition point

- ( ) Use behavior from Criteria/Bimetallic Conductor Model
- ( ) Aluminum does not take compression at high temperature (Bird Cage)
- (•) Aluminum can go into compression at high temperature

VirtualStress = ActualStress * Ao / At
Ao = cross section area of outer strands
At = total cross section area of entire conductor (outer + inner strands)

Maximum virtual compressive stress (ksi): 1.25

Thermal Rating Properties

Resistance at two different temperatures

Resistance (Ohm/mile)	0.0461	at (deg F)	68
Resistance (Ohm/mile)	0.056	at (deg F)	167

Emissivity coefficient	0.5
Solar absorption coefficient	0.5
Outer strands heat capacity (Watt-s/ft-deg F)	436.8
Core heat capacity (Watt-s/ft-deg F)	23.6

[Generate Coefficients from points on stress-strain curve] [Composite cable properties] [OK] [Cancel]

POWER ENGINEERS

600 kV DC Bipolar -Clean Line

APPENDIX I- Preliminary Conductors Comparison Summary Table: MOT vs. Ampacity and Power

Conductor Type	Normal Regime; 2 ft/s wind Calculated Neccesary MOT for: P rectifier=3720 MW P pole=1860 MW I pole=3100 A I conductor=1033.3 A [2]	Emergency Regime [1]; 2 ft/s wind Calculated Neccesary MOT for: P rectifier=4092 MW [1] P pole=2046 MW [1] I pole=3400 A [1] I conductor=1133.3 A [1, 2]	Normal Regime; 0 ft/s wind Calculated Neccesary MOT for: P rectifier=3720 MW P pole=1860 MW I pole=3100 A I conductor=1033.3 A [2]	Emergency Regime [1]; 0 ft/s wind Calculated Neccesary MOT for: P rectifier=4092 MW [1] P pole=2046 MW [1] I pole=3400 A [1] I conductor=1133.3 A [1, 2]	Normal Regime; 2 ft/s wind Neccesary Power (Current) to reach: MOT=284 F=140 C (MAX.)
Biggest ACSR Bluebird 2156 kCMIL	MOT=148 F= 64 C Max. Sag=58.98 ft at MOT=148 F=64 C, Final in Ruling Span=1500 ft	MOT=154 F= 68 C	MOT=173 F= 78 C	MOT=180 F= 82 C	For Bluebird conductor to reach MOT=284 F= 140 C (MAX.) results it is neccesary: P rectifier=8914 MW (very high!) P pole=4457 MW I pole=7428 A I conductor=2476 A [2] Max. Sag=68.57 ft at MOT=284 F=140 C, Final in Ruling Span=1500 ft Difference in Max Sag=9.59 ft between Max MOT=140 C and Neccesary MOT=64 C
Smallest ACSR Bittern 1272 kCMIL	MOT=175 F= 79 C Max. Sag=64.08 ft at MOT=175 F=79 C, Final in Ruling Span=1500 ft	MOT=186 F= 86 C	MOT=214 F= 101 C	MOT=230 F= 110 C	For Bittern conductor to reach MOT=284 F= 140 C (MAX.) results it is neccesary: P rectifier=6170 MW (very high!) P pole=3085 MW I pole=5142 A I conductor=1714 A [2] Max. Sag=70.02 ft at MOT=284 F=140 C, Final in Ruling Span=1500 ft Difference in Max Sag=5.94 ft between Max MOT=140 C and Neccesary MOT=79 C

Notes: 1) Emergency Regime: 10% higher than Normal Regime. 2) Assumed 3 conductors/pole.

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ACSR BlueBird @ MOT=148 F=64 C for Normal Regime, Ampacity=1033.3 A
Rling Span=1500 ft
Max Sag @ MOT=148 F=64 C, Final=58.98 ft

Conductor: 2156.0 Kcmil 84/19 Stranding ACSR "BLUEBIRD"

Area = 1.8309 Sq. in Diameter = 1.762 in Weight = 2.511 lb/ft RTS = 60300 lb
Data from Chart No. 1-1020
English Units
Limits and Outputs in Average Tensions.

Span = 1500.0 Feet
Creep IS a Factor

Customary Heavy Load Zone
Rolled Rod

Design Points						Final			Initial	
Temp °F	Ice in	Wind psf	K lb/ft	Weight lb/ft	Sag Ft	Tension lb	RTS %	Sag Ft	Tension lb	RTS %
0.0	0.50	4.00	0.30	4.324	51.53	23714	39.3	47.16	25891	42.9
15.0	1.25	4.10	0.00	7.339	58.38	35571	59.0	57.72	35975	59.7
32.0	0.50	0.00	0.00	3.917	53.07	20866	34.6	47.84	23126	38.4
60.0	0.00	24.30	0.00	4.363	56.07	22008	36.5	51.19	24084	39.9
-20.0	0.00	0.00	0.00	2.511	45.27	15655	26.0	38.24	18515	30.7
0.0	0.00	0.00	0.00	2.511	47.03	15075	25.0*	39.89	17756	29.4
30.0	0.00	0.00	0.00	2.511	49.60	14301	23.7	42.36	16727	27.7
60.0	0.00	0.00	0.00	2.511	52.09	13623	22.6	44.82	15814	26.2
90.0	0.00	0.00	0.00	2.511	54.51	13025	21.6	47.25	15006	24.9
120.0	0.00	0.00	0.00	2.511	56.85	12494	20.7	49.65	14287	23.7
148.0	0.00	0.00	0.00	2.511	58.98	12049	20.0	51.85	13687	22.7

* Design Condition

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ACSR Bittern @ MOT=284 F=140 C (Max Allowed for ACSR)
Ruling Span=1500 ft
Max Sag @ MOT=284 F=140 C, Final=70.02 ft

Conductor: 1272.0 Kcmil 45/ 7 Stranding ACSR "BITTERN"

Area = 1.0680 Sq. in Diameter = 1.345 in Weight = 1.434 lb/ft RTS = 34100 lb
Data from Chart No. 1-957
English Units
Limits and Outputs in Average Tensions.

Span = 1500.0 Feet — Customary Heavy Load Zone
Creep is NOT a Factor — Rolled Rod

Design Points					Final			Initial		
Temp °F	Ice in	Wind psf	K lb/ft	Weight lb/ft	Sag Ft	Tension lb	RTS %	Sag Ft	Tension lb	RTS %
0.0	0.50	4.00	0.30	2.997	55.96	15146	44.4	49.65	17050	50.0*
15.0	1.25	4.10	0.00	5.623	64.08	24862	72.9	64.08	24862	72.9
32.0	0.50	0.00	0.00	2.581	56.99	12812	37.6	49.25	14803	43.4
60.0	0.00	24.30	0.00	3.078	60.49	14404	42.2	53.69	16206	47.5
-20.0	0.00	0.00	0.00	1.434	48.54	8343	24.5	37.53	10773	31.6
0.0	0.00	0.00	0.00	1.434	50.29	8056	23.6	39.21	10313	30.2
30.0	0.00	0.00	0.00	1.434	52.83	7672	22.5	41.75	9690	28.4
60.0	0.00	0.00	0.00	1.434	55.30	7333	21.5	44.27	9141	26.8
90.0	0.00	0.00	0.00	1.434	57.69	7033	20.6	46.77	8658	25.4
120.0	0.00	0.00	0.00	1.434	60.00	6765	19.8	49.22	8230	24.1
284.0	0.00	0.00	0.00	1.434	70.02	5810	17.0	61.70	6581	19.3

* Design Condition

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ACSR Bittern @ MOT=175 F=79 C for Normal Regime, Ampacity=1033.3 A
Ruling Span=1500 ft
Max Sag @ MOT=175 F=79 C, Final=62.10 ft

Conductor: 1272.0 Kcmil 45/ 7 Stranding ACSR "BITTERN"

Area = 1.0680 Sq. in Diameter = 1.345 in Weight = 1.434 lb/ft RTS = 34100 lb
Data from Chart No. 1-957
English Units
Limits and Outputs in Average Tensions.

Span = 1500.0 Feet Customary Heavy Load Zone
Creep is NOT a Factor Rolled Rod

Design Points						Final			Initial	
Temp °F	Ice in	Wind psf	K lb/ft	Weight lb/ft	Sag Ft	Tension lb	RTS %	Sag Ft	Tension lb	RTS %
0.0	0.50	4.00	0.30	2.997	55.96	15146	44.4	49.65	17050	50.0*
15.0	1.25	4.10	0.00	5.623	64.08	24862	72.9	64.08	24862	72.9
32.0	0.50	0.00	0.00	2.581	56.99	12812	37.6	49.25	14803	43.4
60.0	0.00	24.30	0.00	3.078	60.49	14404	42.2	53.69	16206	47.5
-20.0	0.00	0.00	0.00	1.434	48.54	8343	24.5	37.53	10773	31.6
0.0	0.00	0.00	0.00	1.434	50.29	8056	23.6	39.21	10313	30.2
30.0	0.00	0.00	0.00	1.434	52.83	7672	22.5	41.75	9690	28.4
60.0	0.00	0.00	0.00	1.434	55.30	7333	21.5	44.27	9141	26.8
90.0	0.00	0.00	0.00	1.434	57.69	7033	20.6	46.77	8658	25.4
120.0	0.00	0.00	0.00	1.434	60.00	6765	19.8	49.22	8230	24.1
148.0	0.00	0.00	0.00	1.434	62.10	6539	19.2	51.46	7874	23.1

* Design Condition

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Power Engineers

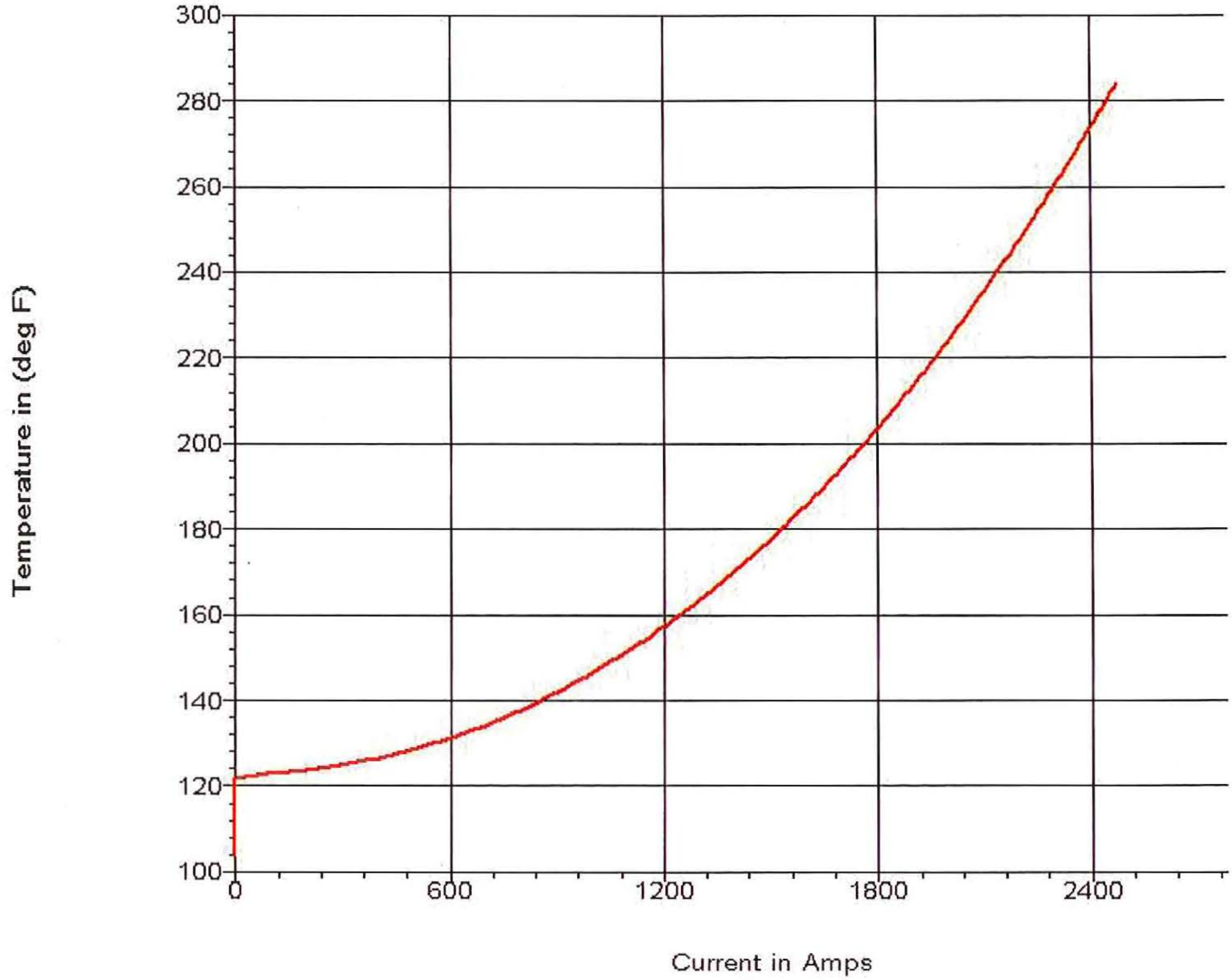
IEEE Std. 738-2006 method of calculation

Air temperature is 104.00 (deg F)=40 (deg C)
Wind speed is 2.00 (ft/s)
Angle between wind and conductor is 90 (deg)
Conductor elevation above sea level is 1000 (ft)
Conductor bearing is -7 (deg) (perpendicular to solar azimuth for maximum solar heating)
Sun time is 14 hours (solar altitude is 63 deg. and solar azimuth is -97 deg.)
Conductor latitude is 30.0 (deg)
Atmosphere is CLEAR
Day of year is 172 (corresponds to June 21 in year 2010) (day of the year with most solar heating)

Conductor description: 2156 kcmil 84/19 Strands BLUEBIRD ACSR - Adapted from 1970's Publicly Available Data
Conductor diameter is 1.762 (in)
Conductor resistance is 0.0423 (Ohm/mile) at 68.0 (deg F)
and 0.0499 (Ohm/mile) at 167.0 (deg F)
Emissivity is 0.5 and solar absorptivity is 0.5

Solar heat input is 7.105 (Watt/ft) (corresponds to Global Solar Radiation of 96.778 (Watt/ft^2) - which was calculated)
Radiation cooling is 23.703 (Watt/ft)
Convective cooling is 51.773 (Watt/ft)

Given a constant ac current of 2476.0 amperes,
The conductor temperature is 284.0 (deg F)=140 (deg C)



300
280
260
240
220
200
180
160
140
120
100
Temperature in (deg F)
0
600
1200
1800
2400
Current in Amps

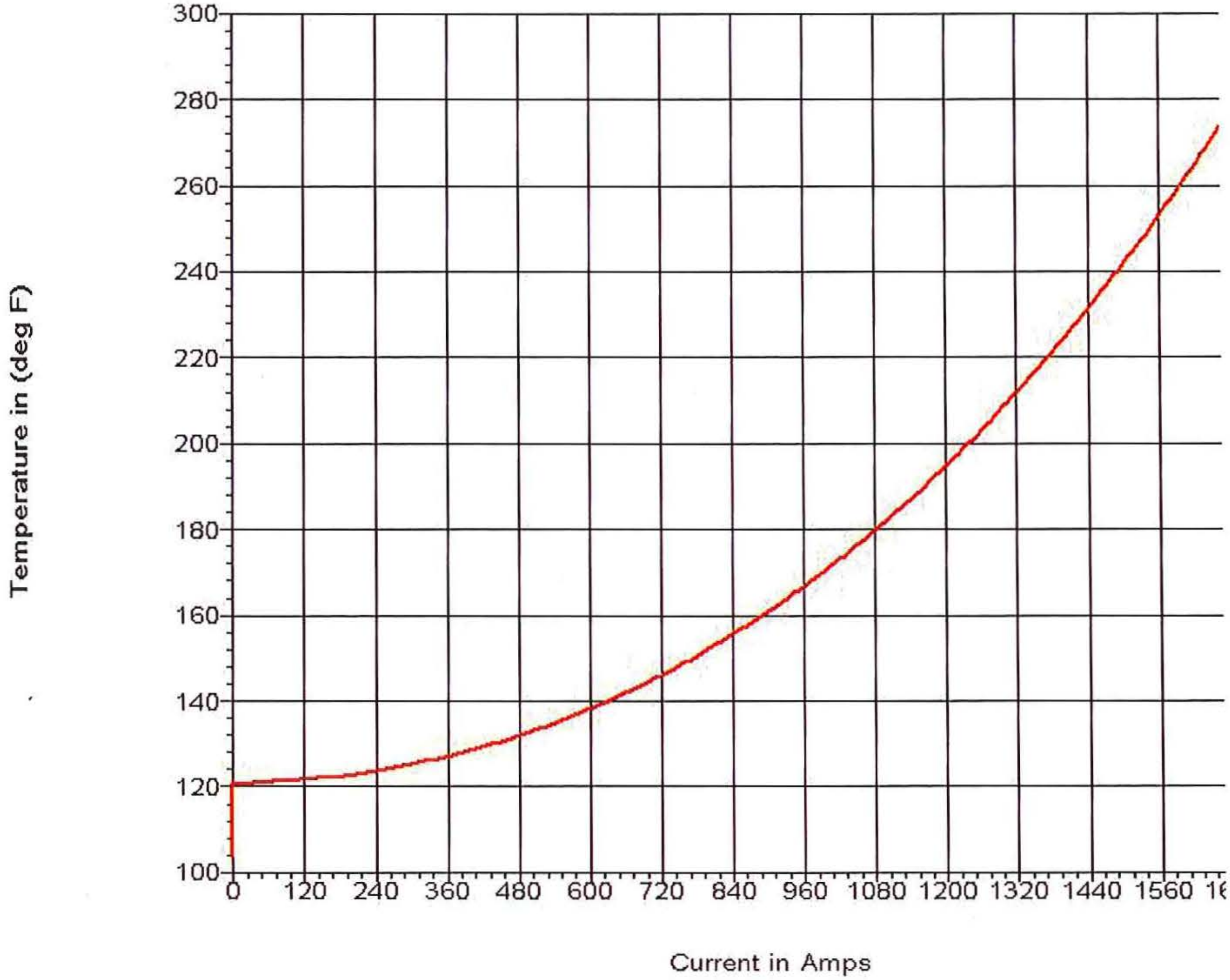
IEEE Std. 738-2006 method of calculation

Air temperature is 104.00 (deg F)=40 9deg C)
Wind speed is 2.00 (ft/s)
Angle between wind and conductor is 90 (deg)
Conductor elevation above sea level is 1000 (ft)
Conductor bearing is -7 (deg) (perpendicular to solar azimuth for maximum solar heating)
Sun time is 14 hours (solar altitude is 63 deg. and solar azimuth is -97 deg.)
Conductor latitude is 30.0 (deg)
Atmosphere is CLEAR
Day of year is 172 (corresponds to June 21 in year 2010) (day of the year with most solar heating)

Conductor description: 1272 kcmil 45/7 Strands BITTERN ACSR - Adapted from 1970's Publicly Available Data
Conductor diameter is 1.345 (in)
Conductor dc resistance is   0.0714 (Ohm/mile) at 68.0 (deg F)
and   0.0863 (Ohm/mile) at 167.0 (deg F)
Emissivity is 0.5 and solar absorptivity is 0.5

Solar heat input is   5.424 (Watt/ft) (corresponds to Global Solar Radiation of 96.778 (Watt/ft^2) - which was calculated)
Radiation cooling is   18.109 (Watt/ft)
Convective cooling is   45.141 (Watt/ft)

Given a constant ac current of 1714.0 amperes,
The conductor temperature is 284.1 (deg F)=140 (deg C)


300
280
260
240
220
200
180
160
140
120
100
Temperature in (deg F)
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
Current in Amps

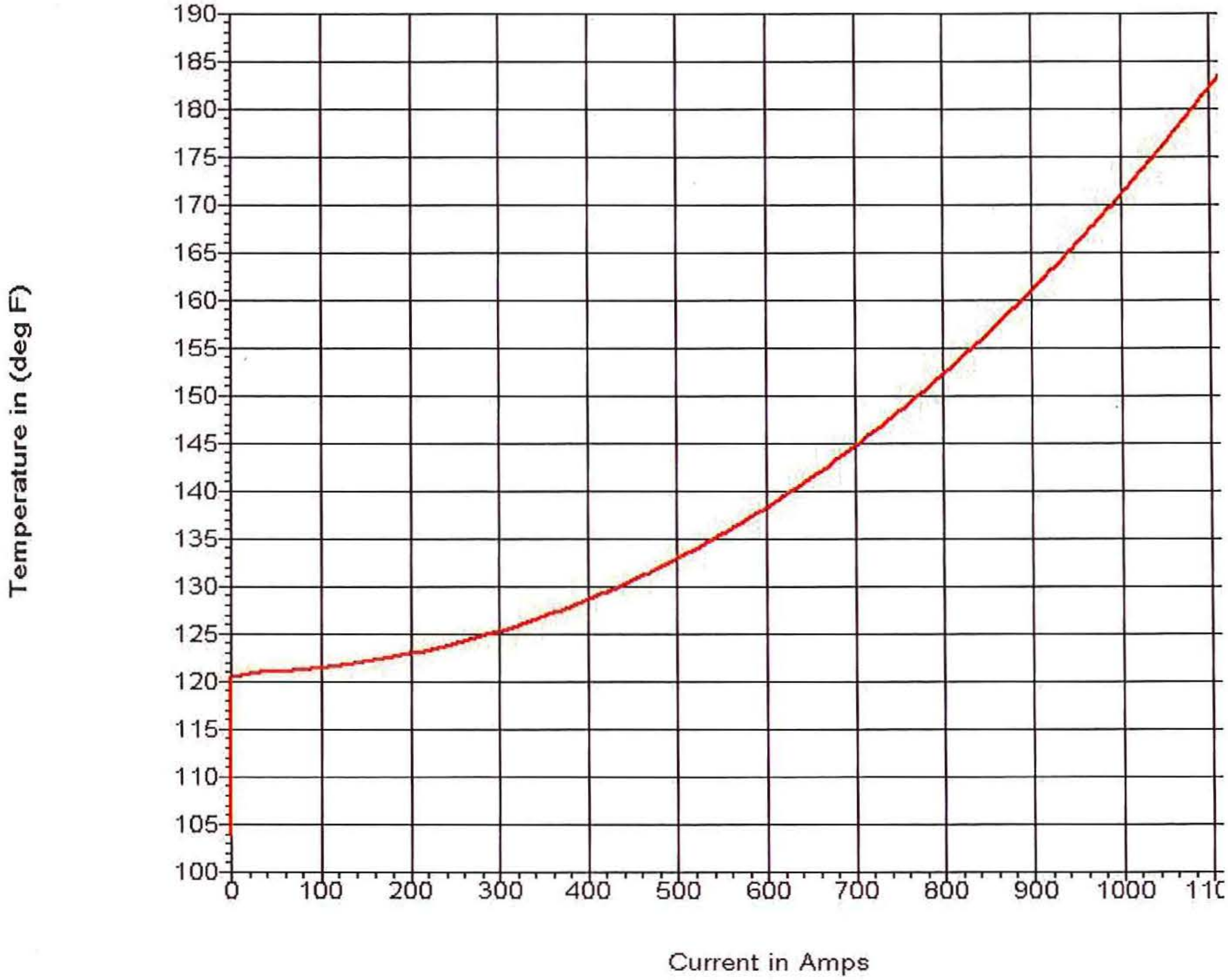
IEEE Std. 738-2006 method of calculation

Air temperature is 104.00 (deg F)=40 (deg C)
Wind speed is 2.00 (ft/s)
Angle between wind and conductor is 90 (deg)
Conductor elevation above sea level is 1000 (ft)
Conductor bearing is -7 (deg) (perpendicular to solar azimuth for maximum solar heating)
Sun time is 14 hours (solar altitude is 63 deg. and solar azimuth is -97 deg.)
Conductor latitude is 30.0 (deg)
Atmosphere is CLEAR
Day of year is 172 (corresponds to June 21 in year 2010) (day of the year with most solar heating)

Conductor description: 1272 kcmil 45/7 Strands BITTERN ACSR - Adapted from 1970's Publicly Available Data
Conductor diameter is 1.345 (in)
Conductor dc resistance is 0.0714 (Ohm/mile) at 68.0 (deg F)
and 0.0863 (Ohm/mile) at 167.0 (deg F)
Emissivity is 0.5 and solar absorptivity is 0.5

Solar heat input is 5.424 (Watt/ft) (corresponds to Global Solar Radiation of 96.778 (Watt/ft^2) - which was calculated)
Radiation cooling is 6.460 (Watt/ft)
Convective cooling is 20.662 (Watt/ft)

Given a constant ac current of 1133.3 amperes,
The conductor temperature is 186.3 (deg F)=86 (deg C)



190
185
180
175
170
165
160
155
150
145
140
135
130
125
120
115
110
105
100
Temperature in (deg F)
0
100
200
300
400
500
600
700
800
900
1000
110
Current in Amps

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Power Engineers

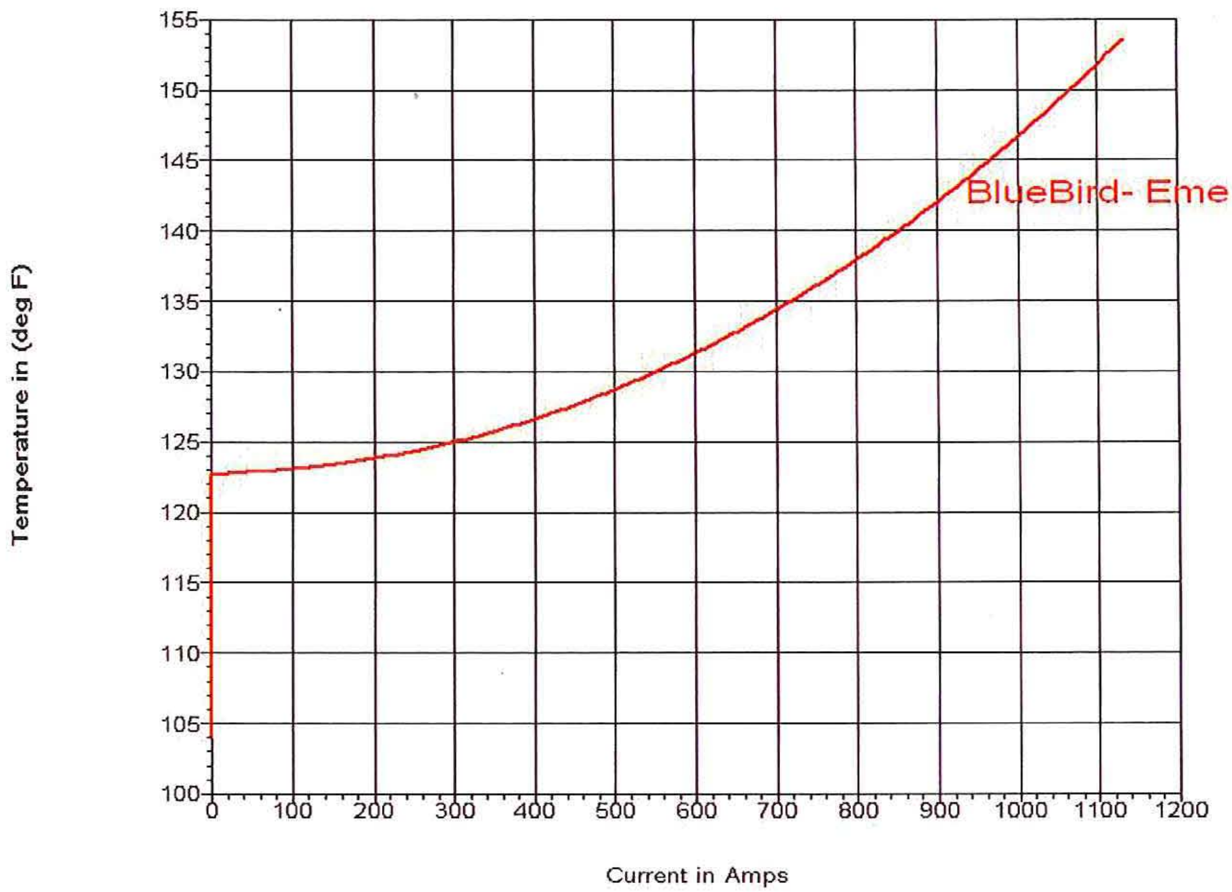
IEEE Std. 738-2006 method of calculation

Air temperature is 104.00 (deg F)=40 (deg C)
Wind speed is 2.00 (ft/s)
Angle between wind and conductor is 90 (deg)
Conductor elevation above sea level is 1000 (ft)
Conductor bearing is -7 (deg) (perpendicular to solar azimuth for maximum solar heating)
Sun time is 14 hours (solar altitude is 63 deg. and solar azimuth is -97 deg.)
Conductor latitude is 30.0 (deg)
Atmosphere is CLEAR
Day of year is 172 (corresponds to June 21 in year 2010) (day of the year with most solar heating)

Conductor description: 2156 kcmil 84/19 Strands BLUEBIRD ACSR - Adapted from 1970's Publicly Available Data
Conductor diameter is 1.762 (in)
Conductor resistance is 0.0423 (Ohm/mile) at 68.0 (deg F)
and 0.0499 (Ohm/mile) at 167.0 (deg F)
Emissivity is 0.5 and solar absorptivity is 0.5

Solar heat input is 7.105 (Watt/ft) (corresponds to Global Solar Radiation of 96.778 (Watt/ft^2) - which was calculated)
Radiation cooling is 4.685 (Watt/ft)
Convective cooling is 14.307 (Watt/ft)

Given a constant ac current of 1133.3 amperes,
The conductor temperature is 153.6 (deg F)=68 (deg C)


155
150
145
140
135
130
125
120
115
110
105
100
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
BlueBird- Eme
Temperature in (deg F)
Current in Amps

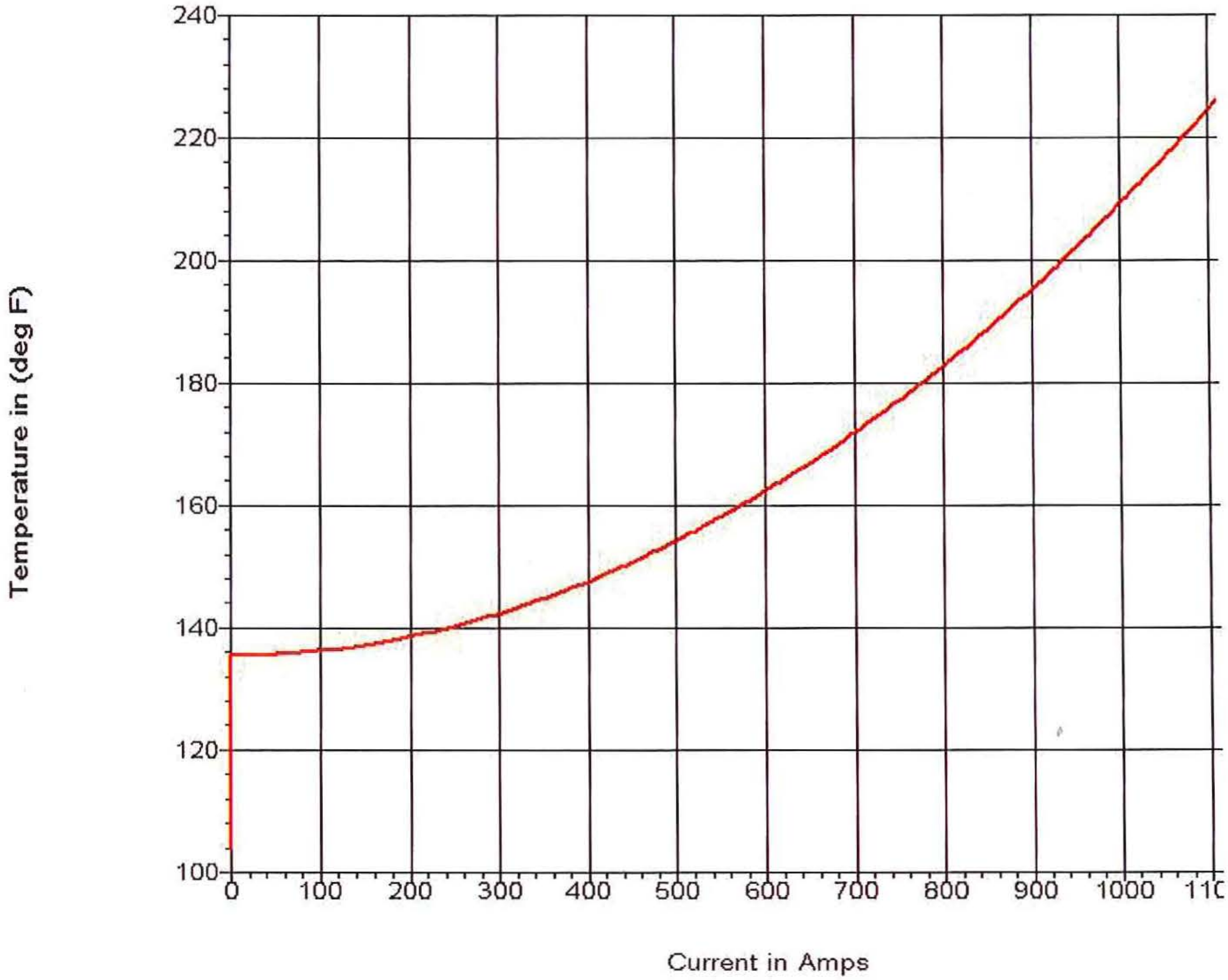
IEEE Std. 738-2006 method of calculation

Air temperature is 104.00 (deg F)=40 (deg C)
Wind speed is 0.00 (ft/s)
Angle between wind and conductor is 90 (deg)
Conductor elevation above sea level is 1000 (ft)
Conductor bearing is -7 (deg) (perpendicular to solar azimuth for maximum solar heating)
Sun time is 14 hours (solar altitude is 63 deg. and solar azimuth is -97 deg.)
Conductor latitude is 30.0 (deg)
Atmosphere is CLEAR
Day of year is 172 (corresponds to June 21 in year 2010) (day of the year with most solar heating)

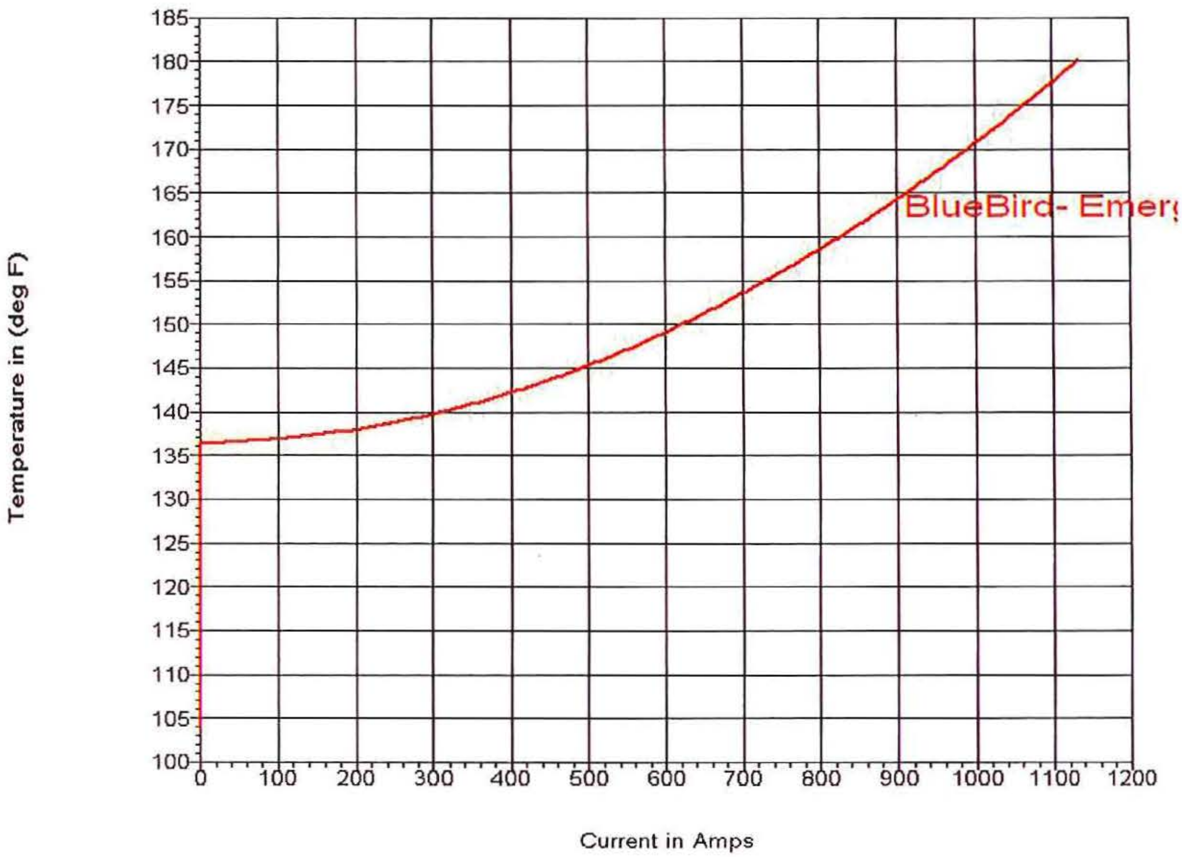
Conductor description: 1272 kcmil 45/7 Strands BITTERN ACSR - Adapted from 1970's Publicly Available Data
Conductor diameter is 1.345 (in)
Conductor dc resistance is 0.0714 (Ohm/mile) at 68.0 (deg F)
and 0.0863 (Ohm/mile) at 167.0 (deg F)
Emissivity is 0.5 and solar absorptivity is 0.5

Solar heat input is 5.424 (Watt/ft) (corresponds to Global Solar Radiation of 96.778 (Watt/ft^2) - which was calculated)
Radiation cooling is 11.053 (Watt/ft)
Convective cooling is 17.666 (Watt/ft)

Given a constant ac current of 1133.3 amperes,
The conductor temperature is 229.9 (deg F)=110 (deg C)


240
220
200
180
160
140
120
100
Temperature in (deg F)
0
100
200
300
400
500
600
700
800
900
1000
110
Current in Amps

```
PLS-CADD Version 10.60x64    2:35:36 PM Tuesday, August 10, 2010
Power Engineers

IEEE Std. 738-2006 method of calculation

Air temperature is 104.00 (deg F)=40 (deg C)
Wind speed is 0.00 (ft/s)
Angle between wind and conductor is 90 (deg)
Conductor elevation above sea level is 1000 (ft)
Conductor bearing is -7 (deg) (perpendicular to solar azimuth for maximum solar
heating)
Sun time is 14 hours (solar altitude is 63 deg. and solar azimuth is -97 deg.)
Conductor latitude is 30.0 (deg)
Atmosphere is CLEAR
Day of year is 172 (corresponds to June 21 in year 2010) (day of the year with
most solar heating)

Conductor description: 2156 kcmil 84/19 Strands BLUEBIRD ACSR - Adapted from 1970's
Publicly Available Data
Conductor diameter is 1.762 (in)
Conductor resistance is     0.0423 (Ohm/mile) at  68.0 (deg F)
                    and     0.0499 (Ohm/mile) at 167.0 (deg F)
Emissivity is 0.5 and solar absorptivity is 0.5

Solar heat input is      7.105 (Watt/ft) (corresponds to Global Solar Radiation
of   96.778 (Watt/ft^2) - which was calculated)
Radiation cooling is     7.711 (Watt/ft)
Convective cooling is   11.779 (Watt/ft)

Given a constant ac current of 1133.3 amperes,
The conductor temperature is 180.2 (deg F)=82 (deg C)
```



185
180
175
170
165
160
155
150
145
140
135
130
125
120
115
110
105
100
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
Temperature in (deg F)
Current in Amps
BlueBird- Emer

Southwire SAG10™

8/11/2010

Power engineers

ACSR Bittern @ MOT=175 F=79 C for Normal Regime, Ampacity=1033.3 A
Ruling Span=1500 ft
Max Sag @ MOT=175 F=79 C, Final=64.08 ft

Conductor: 1272.0 Kcmil 45/ 7 Stranding ACSR "BITTERN"

Area = 1.0680 Sq. in Diameter = 1.345 in Weight = 1.434 lb/ft RTS = 34100 lb
Data from Chart No. 1-957
English Units
Limits and Outputs in Average Tensions.

Span = 1500.0 Feet Special Load Zone
Creep is NOT a Factor Rolled Rod

Design Points					Final			Initial		
Temp °F	Ice in	Wind psf	K lb/ft	Weight lb/ft	Sag Ft	Tension lb	RTS %	Sag Ft	Tension lb	RTS %
0.0	0.50	4.00	0.30	2.997	55.96	15146	44.4	49.65	17050	50.0*
15.0	1.25	4.10	0.00	5.623	64.08	24862	72.9	64.08	24862	72.9
32.0	0.50	0.00	0.00	2.581	56.99	12812	37.6	49.25	14803	43.4
60.0	0.00	24.30	0.00	3.078	60.49	14404	42.2	53.69	16206	47.5
-20.0	0.00	0.00	0.00	1.434	48.54	8343	24.5	37.53	10773	31.6
0.0	0.00	0.00	0.00	1.434	50.29	8056	23.6	39.21	10313	30.2
30.0	0.00	0.00	0.00	1.434	52.83	7672	22.5	41.75	9690	28.4
60.0	0.00	0.00	0.00	1.434	55.30	7333	21.5	44.27	9141	26.8
90.0	0.00	0.00	0.00	1.434	57.69	7033	20.6	46.77	8658	25.4
120.0	0.00	0.00	0.00	1.434	60.00	6765	19.8	49.22	8230	24.1
175.0	0.00	0.00	0.00	1.434	64.08	6340	18.6	53.58	7566	22.2

* Design Condition

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Power Engineers

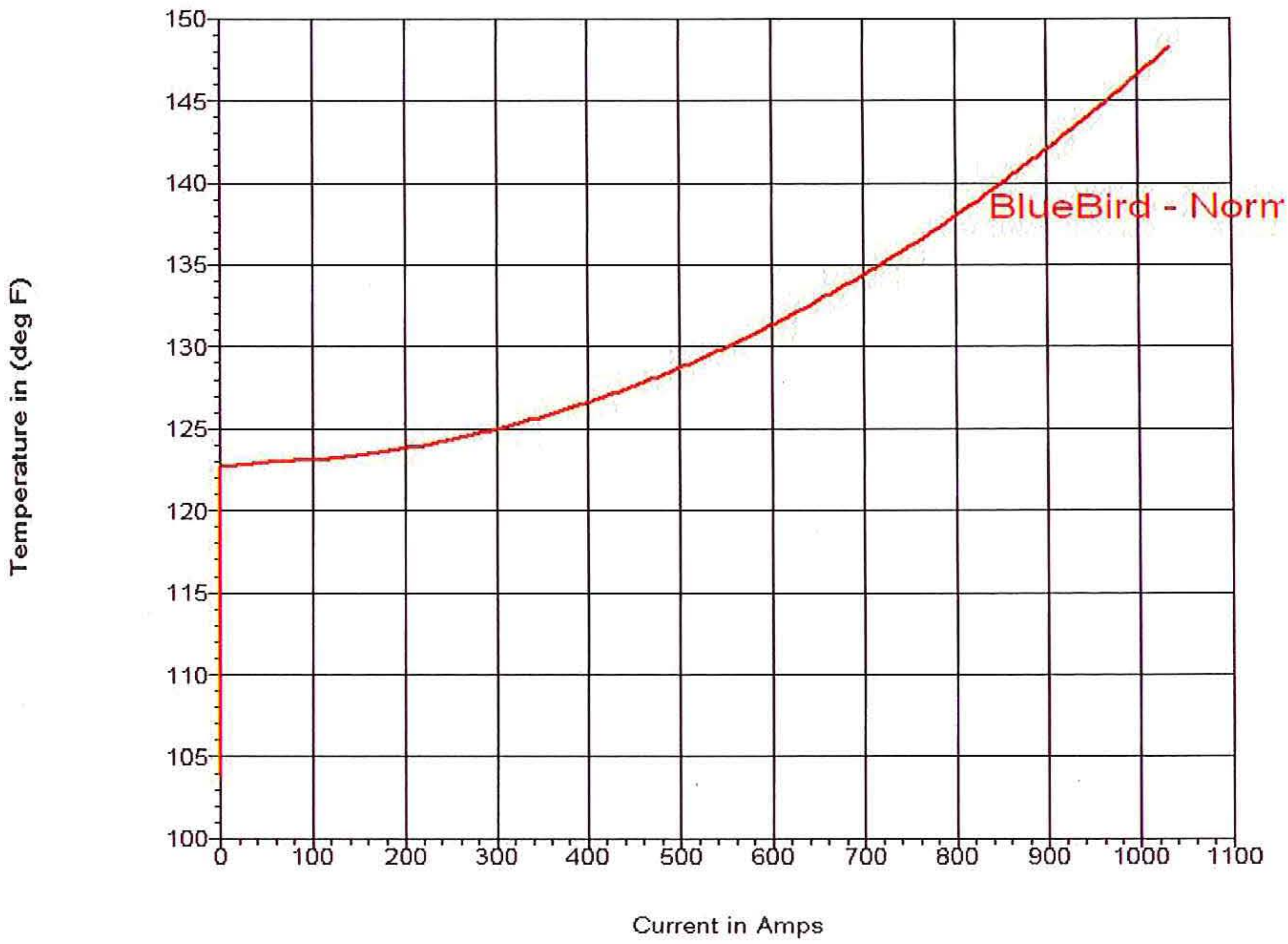
IEEE Std. 738-2006 method of calculation

Air temperature is 104.00 (deg F)=40 (deg C)
Wind speed is 2.00 (ft/s)
Angle between wind and conductor is 90 (deg)
Conductor elevation above sea level is 1000 (ft)
Conductor bearing is -7 (deg) (perpendicular to solar azimuth for maximum solar heating)
Sun time is 14 hours (solar altitude is 63 deg. and solar azimuth is -97 deg.)
Conductor latitude is 30.0 (deg)
Atmosphere is CLEAR
Day of year is 172 (corresponds to June 21 in year 2010) (day of the year with most solar heating)

Conductor description: 2156 kcmil 84/19 Strands BLUEBIRD ACSR - Adapted from 1970's Publicly Available Data
Conductor diameter is 1.762 (in)
Conductor resistance is 0.0423 (Ohm/mile) at 68.0 (deg F)
and 0.0499 (Ohm/mile) at 167.0 (deg F)
Emissivity is 0.5 and solar absorptivity is 0.5

Solar heat input is 7.105 (Watt/ft) (corresponds to Global Solar Radiation of 96.778 (Watt/ft^2) - which was calculated)
Radiation cooling is 4.127 (Watt/ft)
Convective cooling is 12.782 (Watt/ft)

Given a constant ac current of 1033.3 amperes,
The conductor temperature is 148.3 (deg F)=64 (deg C)


BlueBird - Norm
Temperature in (deg F)
150
145
140
135
130
125
120
115
110
105
100
0
100
200
300
400
500
600
700
800
900
1000
1100
Current in Amps

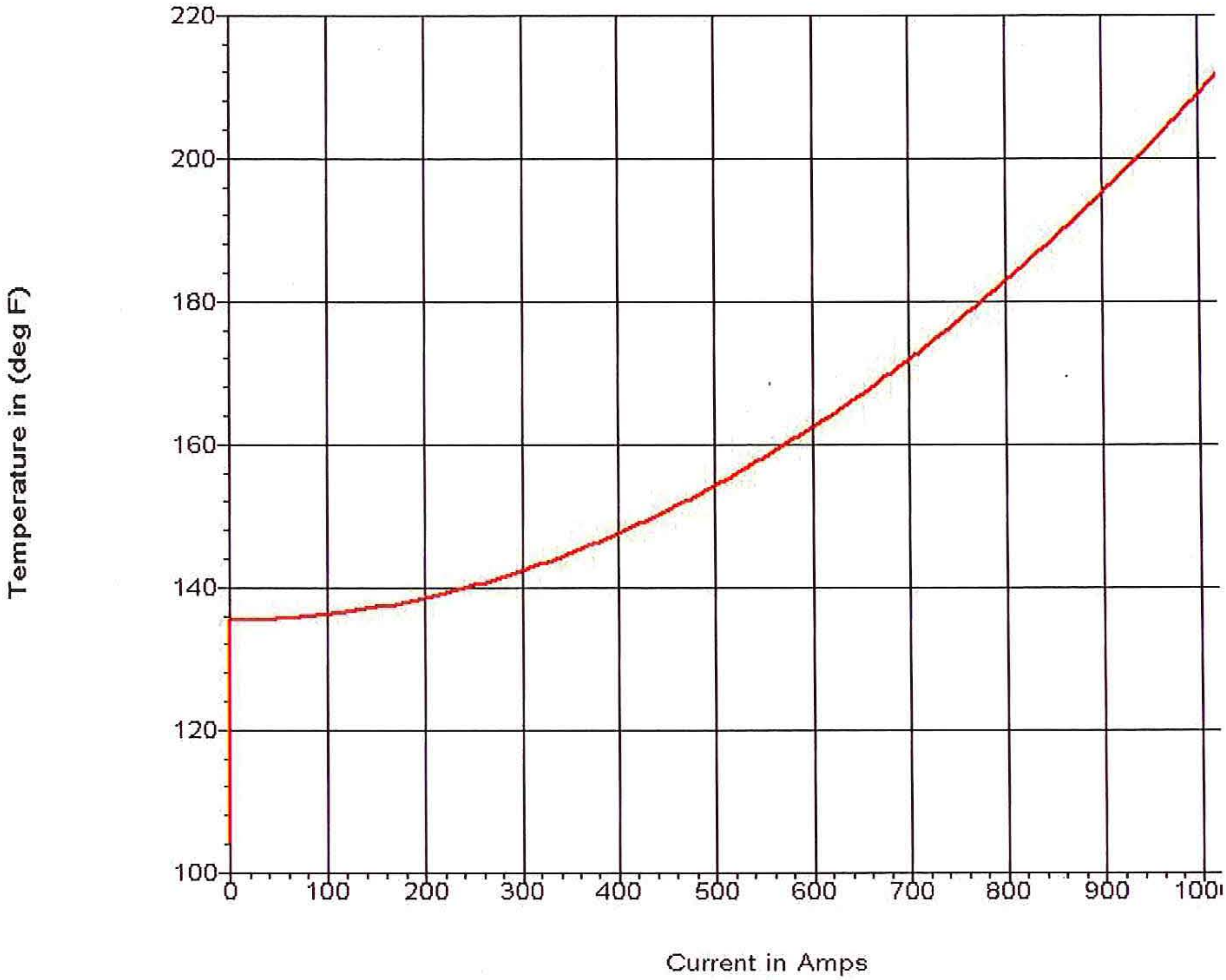
IEEE Std. 738-2006 method of calculation

Air temperature is 104.00 (deg F)=40 (deg C)
Wind speed is 0.00 (ft/s)
Angle between wind and conductor is 90 (deg)
Conductor elevation above sea level is 1000 (ft)
Conductor bearing is -7 (deg) (perpendicular to solar azimuth for maximum solar heating)
Sun time is 14 hours (solar altitude is 63 deg. and solar azimuth is -97 deg.)
Conductor latitude is 30.0 (deg)
Atmosphere is CLEAR
Day of year is 172 (corresponds to June 21 in year 2010) (day of the year with most solar heating)

Conductor description: 1272 kcmil 45/7 Strands BITTERN ACSR - Adapted from 1970's Publicly Available Data
Conductor diameter is 1.345 (in)
Conductor dc resistance is 0.0714 (Ohm/mile) at 68.0 (deg F)
and 0.0863 (Ohm/mile) at 167.0 (deg F)
Emissivity is 0.5 and solar absorptivity is 0.5

Solar heat input is 5.424 (Watt/ft) (corresponds to Global Solar Radiation of 96.778 (Watt/ft^2) - which was calculated)
Radiation cooling is 9.280 (Watt/ft)
Convective cooling is 15.029 (Watt/ft)

Given a constant ac current of 1033.3 amperes,
The conductor temperature is 214.1 (deg F)=101 (deg C)


220
200
180
160
140
120
100
Temperature in (deg F)
0
100
200
300
400
500
600
700
800
900
100
Current in Amps

PLS-CADD Version 10.60x64   2:36:38 PM Tuesday, August 10, 2010
Power Engineers

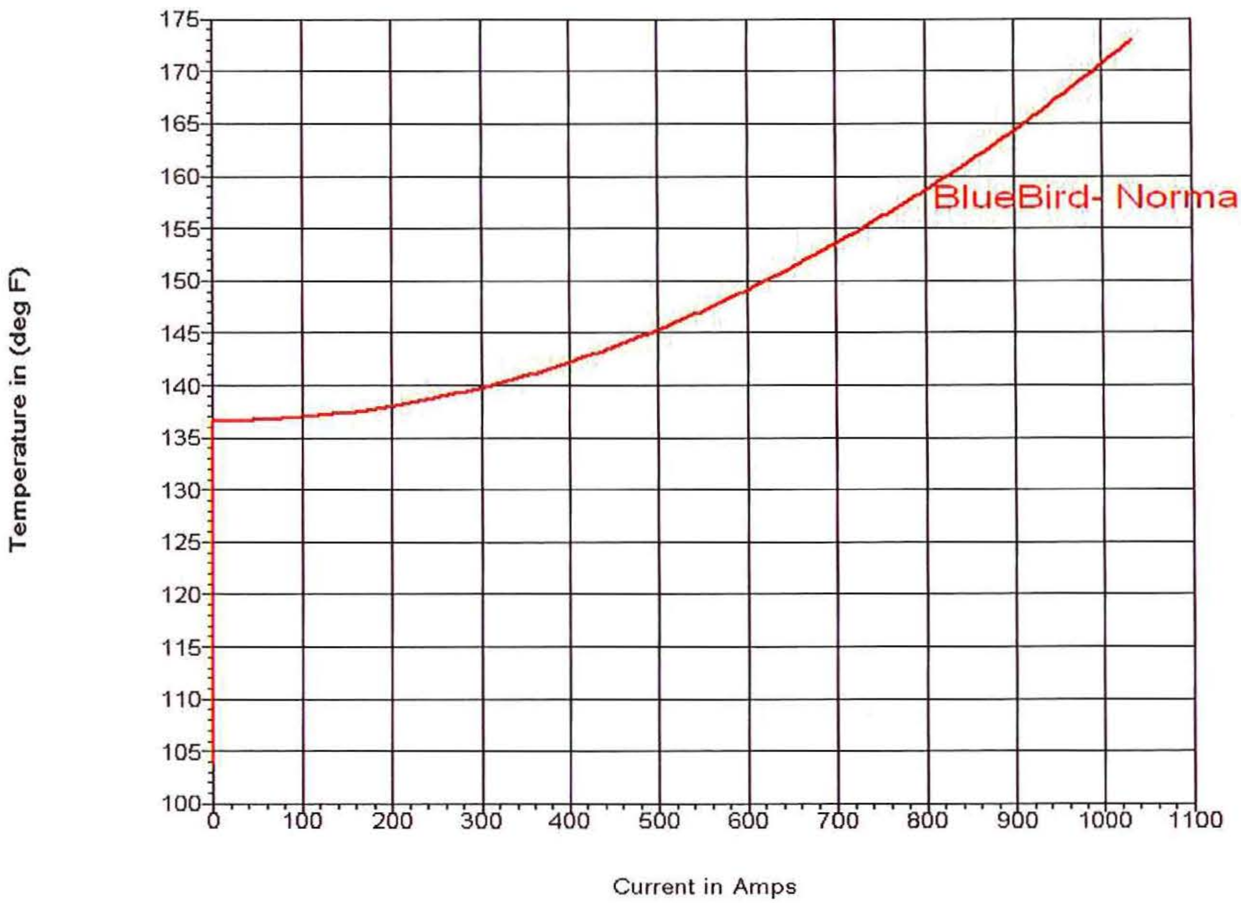
IEEE Std. 738-2006 method of calculation

Air temperature is 104.00 (deg F)=40 (deg C)
Wind speed is 0.00 (ft/s)
Angle between wind and conductor is 90 (deg)
Conductor elevation above sea level is 1000 (ft)
Conductor bearing is -7 (deg) (perpendicular to solar azimuth for maximum solar heating)
Sun time is 14 hours (solar altitude is 63 deg. and solar azimuth is -97 deg.)
Conductor latitude is 30.0 (deg)
Atmosphere is CLEAR
Day of year is 172 (corresponds to June 21 in year 2010) (day of the year with most solar heating)

Conductor description: 2156 kcmil 84/19 Strands BLUEBIRD ACSR - Adapted from 1970's Publicly Available Data
Conductor diameter is 1.762 (in)
Conductor resistance is   0.0423 (Ohm/mile) at 68.0 (deg F)
and   0.0499 (Ohm/mile) at 167.0 (deg F)
Emissivity is 0.5 and solar absorptivity is 0.5

Solar heat input is   7.105 (Watt/ft) (corresponds to Global Solar Radiation of   96.778 (Watt/ft^2) - which was calculated)
Radiation cooling is   6.853 (Watt/ft)
Convective cooling is   10.437 (Watt/ft)

Given a constant ac current of 1033.3 amperes,
The conductor temperature is 173.0 (deg F)=78 (deg C)



Temperature in (deg F)
175
170
165
160
155
150
145
140
135
130
125
120
115
110
105
100
0
100
200
300
400
500
600
700
800
900
1000
1100
BlueBird- Norma
Current in Amps

Southwire SAG10™

8/11/2010

Power engineers

ACSR BlueBird @ MOT=284 F=140 C (Max Allowed for ACSR
Ruling Span=1500 ft
Max Sag @ MOT=284 F=140 C, Final=68.57 ft

Conductor: 2156.0 Kcmil 84/19 Stranding ACSR "BLUEBIRD"

Area = 1.8309 Sq. in Diameter = 1.762 in Weight = 2.511 lb/ft RTS = 60300 lb
Data from Chart No. 1-1020
English Units
Limits and Outputs in Average Tensions.

Span = 1500.0 Feet Customary Heavy Load Zone
Creep IS a Factor Rolled Rod

Design Points						Final			Initial	
Temp °F	Ice in	Wind psf	K lb/ft	Weight lb/ft	Sag Ft	Tension lb	RTS %	Sag Ft	Tension lb	RTS %
0.0	0.50	4.00	0.30	4.324	51.53	23714	39.3	47.16	25891	42.9
15.0	1.25	4.10	0.00	7.339	58.38	35571	59.0	57.72	35975	59.7
32.0	0.50	0.00	0.00	3.917	53.07	20866	34.6	47.84	23126	38.4
60.0	0.00	24.30	0.00	4.363	56.07	22008	36.5	51.19	24084	39.9
-20.0	0.00	0.00	0.00	2.511	45.27	15655	26.0	38.24	18515	30.7
0.0	0.00	0.00	0.00	2.511	47.03	15075	25.0*	39.89	17756	29.4
30.0	0.00	0.00	0.00	2.511	49.60	14301	23.7	42.36	16727	27.7
60.0	0.00	0.00	0.00	2.511	52.09	13623	22.6	44.82	15814	26.2
90.0	0.00	0.00	0.00	2.511	54.51	13025	21.6	47.25	15006	24.9
120.0	0.00	0.00	0.00	2.511	56.85	12494	20.7	49.65	14287	23.7
284.0	0.00	0.00	0.00	2.511	68.57	10386	17.2	61.93	11480	19.0

* Design Condition

POWER ENGINEERS

CLEAN LINE ENERGY: GRAIN BELT EXPRESS +/- 600kV HVDC
FOUNDATION DESIGN CRITERIA

Geotechnical Information:

The foundations will be designed using the soil profiles based on a desktop geotechnical study.

Applied Loading:

The governing intact load cases have an OLF of 1.0 (NESC Extreme Ice w/ Concurrent Wind & NESC Extreme Wind). The broken conductor/conductor stringing load case does govern in some cases and has an OLF of 1.1. This is the predicted load for a broken conductor load and or conductor stringing load therefore the OLF will not be taken out.

Laterally Loaded Drilled Piers:

Foundations will be designed using the design and analysis software MFAD. All foundations will meet the following criteria:

1. Ultimate Load
    a. Factor of safety of 2 with unfactored loads.
2. Allowable Deflection
    a. Maximum tolerable total deflection of 2.0" with unfactored loads.
    b. Maximum tolerable non-recoverable deflection of 0.5" with unfactored loads.
3. Pier Rotation
    a. Maximum tolerable pier rotation of 1.72°.
4. Pier projection of 2.0 ft.
5. Concrete Design
    a. Concrete design strength of 3,000 psi
    b. Concrete strength for construction 4,000 psi.
    c. Longitudinal Reinforcement: #11 bars (60 ksi)
    d. Shear Reinforcement: #4 or #5 ties
    e. 3" clear cover

Note: The allowable deflections for the foundations in some project regions may be adjusted from those shown above to accommodate large variations in subsurface priorities

Uplift and Compression Drilled Piers:

Foundations will be designed with using the design and analysis software SHAFT. All foundations will meet the following criteria:

1. Ultimate load
    a. Shaft determines ultimate load at vertical displacement of foundation diameter divided by 20 (Dia/20).
2. Vertical Displacement (Uplift)
    a. Maximum displacement of 1" with unfactored loads.

3. Vertical Displacement (Compression)
    a. Maximum displacement (settlement) of 1" with unfactored loads.
4. Lateral Performance
    a. The lateral performance of drilled piers shall follow the criteria for laterally loaded drilled piers.
5. Concrete Design
    a. The concrete design shall follow the criteria for lateral loaded drilled piers.

Grain Belt Express HVDC

System Impact Study

Final Report for

Southwest Power Pool

Prepared by:
Excel Engineering, Inc.

September 6, 2013

Principal Contributor:

William Quaintance, P.E.

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0. Certification

I hereby certify that this plan, specification, or report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the Laws of the State of **Kansas**.

William Quaintance
Kansas License Number 20756

Excel Engineering, Inc.
Kansas Firm License Number 1611

1. Background and Scope

The ±600 kV Grain Belt Express (GBX) HVDC line is being developed by Clean Line Energy Partners LLC to transport renewable energy from SPP (near Clark County Substation, Kansas) to AMMO (Palmyra Tap Substation, Missouri) and AEP (Sullivan Substation, Indiana). Clean Line hired Siemens PTI to perform power flow and stability studies of the project's impact on the electric system. SPP hired Excel Engineering to review and repeat the results of the PTI stability study.

Excel analyzed system stability characteristics in the SPP footprint with the GBX HVDC line and renewable generation modeled in the system. The study was performed for select three phase and single line to ground faults at and near the converter stations in three seasonal cases: 2017 light load, 2017 summer peak, and 2022 summer peak. The three seasonal cases were provided by SPP with the HVDC line and wind generation already incorporated into the cases.

This study by Excel Engineering, Inc. consisted of analyzing system stability following faults in the area of the proposed HVDC project as well as providing comments on the project developer's report.

In August 2013, PTI provided new results based on a change in the Point of Interconnection. The new POI is 14 miles closer to Spearville than the previous POI at Clark Co. The new PTI stability results showed the same performance as the original POI. Analysis of the stability of the new POI is included in Section 4.2.2 of this report.

Study assumptions in general have been based on Excel's knowledge of the electric power system and on the specific information and data provided by SPP. The accuracy of the conclusions contained within this study is sensitive to the assumptions made with respect to generation additions and transmission improvements being contemplated. Changes in the assumptions of the timing of other generation additions or transmission improvements will affect this study's conclusions.

2. Executive Summary

The analysis performed by Excel Engineering confirms the results of the PTI stability report. The main conclusions of the report were as follows:

- The worst faults in SPP were N-1-1 and N-2 faults on the parallel 345 kV lines connected to Clark County substation. If one Clark Co – Thistle 345 kV line is out of service and there is a three-phase fault on the parallel line, the GBX wind generators may go unstable and trip off-line by over-frequency protection. The same behavior was seen if one Clark Co – Spearville 345 kV line is out of service and a three-phase fault occurs on the second line.

  The recommendation in the PTI study is to trip up to 877 MW of GBX wind generation after the fault occurs. This solution was confirmed for the original fault list. With an additional N-1-1 fault studied at the Thistle end, up to 1637 MW of wind generation will need to be tripped. However, SPP and the transmission owner will have to decide if a Special Protection System (SPS) such as this would be acceptable.

  An alternative is to reduce the GBX wind generation in a controlled fashion after the first outage occurs, to be prepared in case a fault occurs on the second circuit. Successful performance of this option was also confirmed. However, this option is not available if these double-circuit transmission lines share transmission towers for a significant distance and NERC Category C5 is considered.

  Similar results were found when the SPP POI was changed to a location 14 miles from Clark Co on the Clark Co-Spearville 345 kV lines.

  If neither the post-fault wind tripping SPS nor the pre-fault wind reduction is an acceptable solution, then a major transmission upgrade or reduction in the size of the GBX project will have to be considered.

- The worst faults in AEP were on the Rockport – Jefferson 765 kV line. Outage of this line leaves the 2600 MW Rockport plant feeding radially to Sullivan, the same place where the GBX HVDC converters are injecting 3000 MW. Following this fault, the Rockport generators go unstable and trip. In power flow, the solution diverges for this contingency.

  The recommendation in the PTI study is to trip one of the HVDC poles (1500 MW) after the fault occurs. This solution was confirmed. However, AEP and the transmission owner will have to decide if an SPS such as this would be acceptable.

  If the post-fault HVDC reduction SPS is not an acceptable solution, then a major transmission upgrade or reduction in the size of the GBX project will have to be considered.

- No stability problems were found for faults near the AMMO Palmyra station. The AMMO system is able to handle the additional 500 MW injection without a problem.

Outages of a single pole or both poles of the HVDC line were of particular interest for this study. The analysis confirms stable system response for the faults with loss of one or both poles. It should be noted that only a small portion of generation in the SPP Generator Interconnection Queue in the Spearville, Clark County, and Thistle areas were included in the analysis based on the information provided during the MDWG model development process.

In summary, the following mitigation options were confirmed to eliminate the unstable responses:

- A 900 Mvar Synchronous Condenser was assumed in all cases
- An SPS to reduce GBX wind generation following parallel circuit outages at Clark Co. Up to 1650 MW of wind generation tripping may be needed for certain double line outages.
- An SPS to reduce HVDC power by up to 1500 MW following outage of the Rockport-Jefferson 765 kV line.

It will be critical for the GBX project to maintain a balance in both its MW flow and its Mvar flow. The project is designed to have a normal power exchange with SPP of 0 MW and 0 Mvar. This target needs to be maintained during dynamic conditions as best as possible. Large imbalances can cause voltage violations and generator instability.

Additional considerations for futures studies of the GBX project include:

- Consideration of more breaker failure faults.
- Inclusion of other planned wind generation in the SPP footprint.
- Modeling the maximum 3500 MW HVDC injection at the AEP Sullivan end.
- If the SPS solutions are not acceptable, other solutions such as new transmission lines or reduced GBX project size will have to be found.

The results of this study depend on the assumed models for the HVDC equipment, wind generators, wind collector system, and the power systems in the area of the project. Some of these assumptions will surely change or come into better focus as the project moves forward. The stability analysis will need to be repeated when the assumptions are better defined.

3. Study Development and Assumptions

3.1 Simulation Tools

The Siemens PTI PSS/E power system simulation program Version 30.3.3 was used in this study. The time step used in all simulations was a quarter of a 60 Hz cycle (0.004167s). Simulation duration was as indicated in the fault definition table.

3.2 Models Used

SPP provided the power flow and dynamics models from PTI for 2017 Light Load, 2017 Summer Peak and 2022 Summer Peak conditions. There were also two connection options considered initially at Sullivan, 765 kV and 345 kV, giving a total of six (6) base cases. All other files used to run the original study, such as fault scripts, were also provided by PTI. They were reviewed for accuracy before use in the study.

Figure 3-1 and Figure 3-2 show power flow one-lines for the 2017 Summer Peak case with the 345 kV option at Sullivan and the GBX wind generation model, respectively. One-line diagrams of GBX and the full SPP 345 kV system for all three seasons are provided in Appendix E.

As in the PTI study, all faults in SPP, AMMO, and AEP were run on the cases with the 765 kV connection option at Sullivan. Only faults in AEP were tested with the 345 kV option at Sullivan. It is assumed that the faults in SPP and AMMO would not vary significantly between the two different connection options at AEP's Sullivan station.

Near the end of the study, Clean Line informed SPP that the 765 kV connection option at Sullivan should be dropped from consideration, and only the 345 kV option should be considered. However, most of the simulation work had already been completed. The results of the fault simulations in SPP and AMMO with the 765 kV option in AEP are still considered valid. For faults in AEP, results with the 765 kV option were set aside and only results with the 345 kV option are discussed in this report.

No changes were made to the provided models.

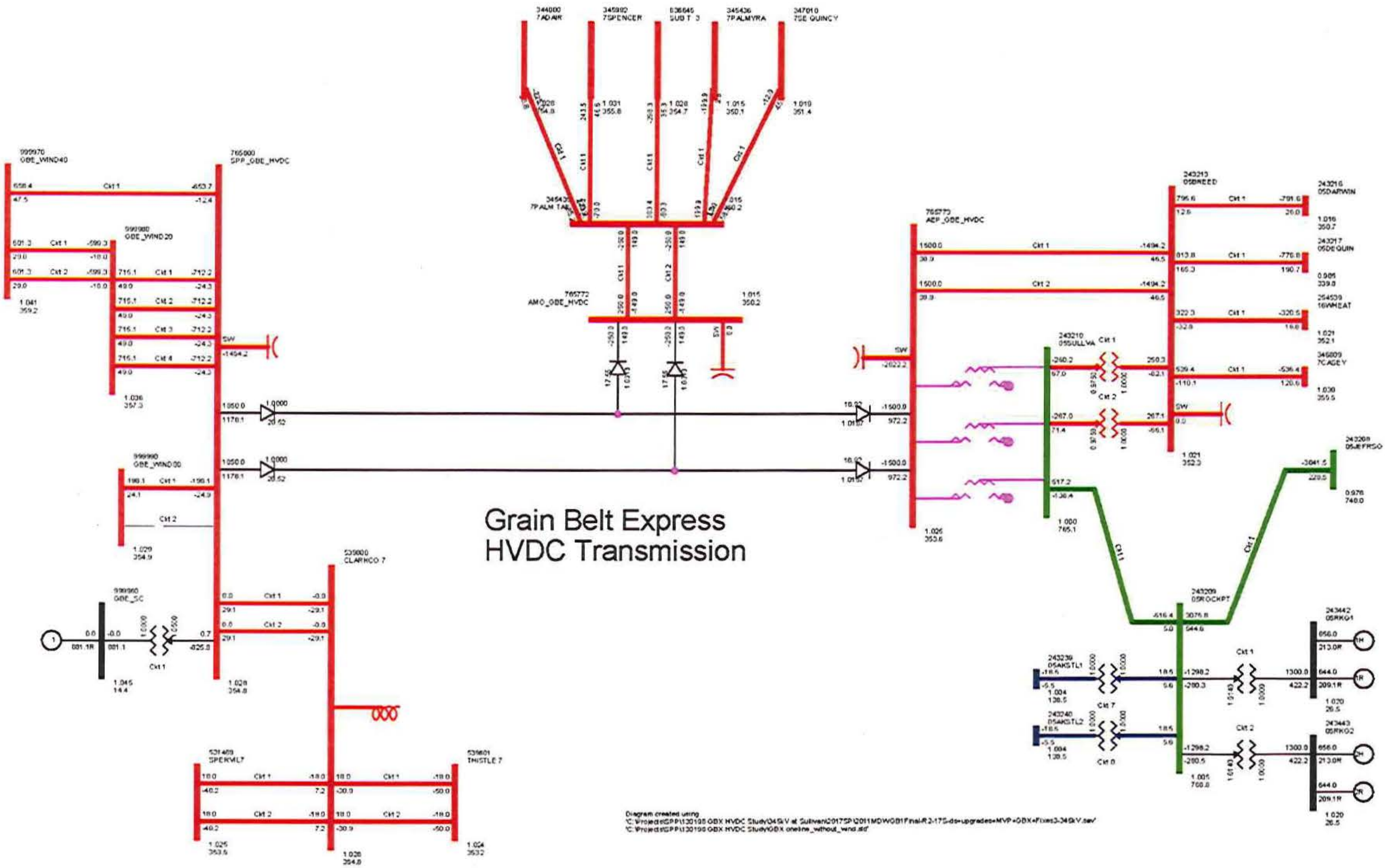


Figure 3-1. Power Flow One-line of GBX HVDC with 345 kV Option at Sullivan – 2017 Summer Peak

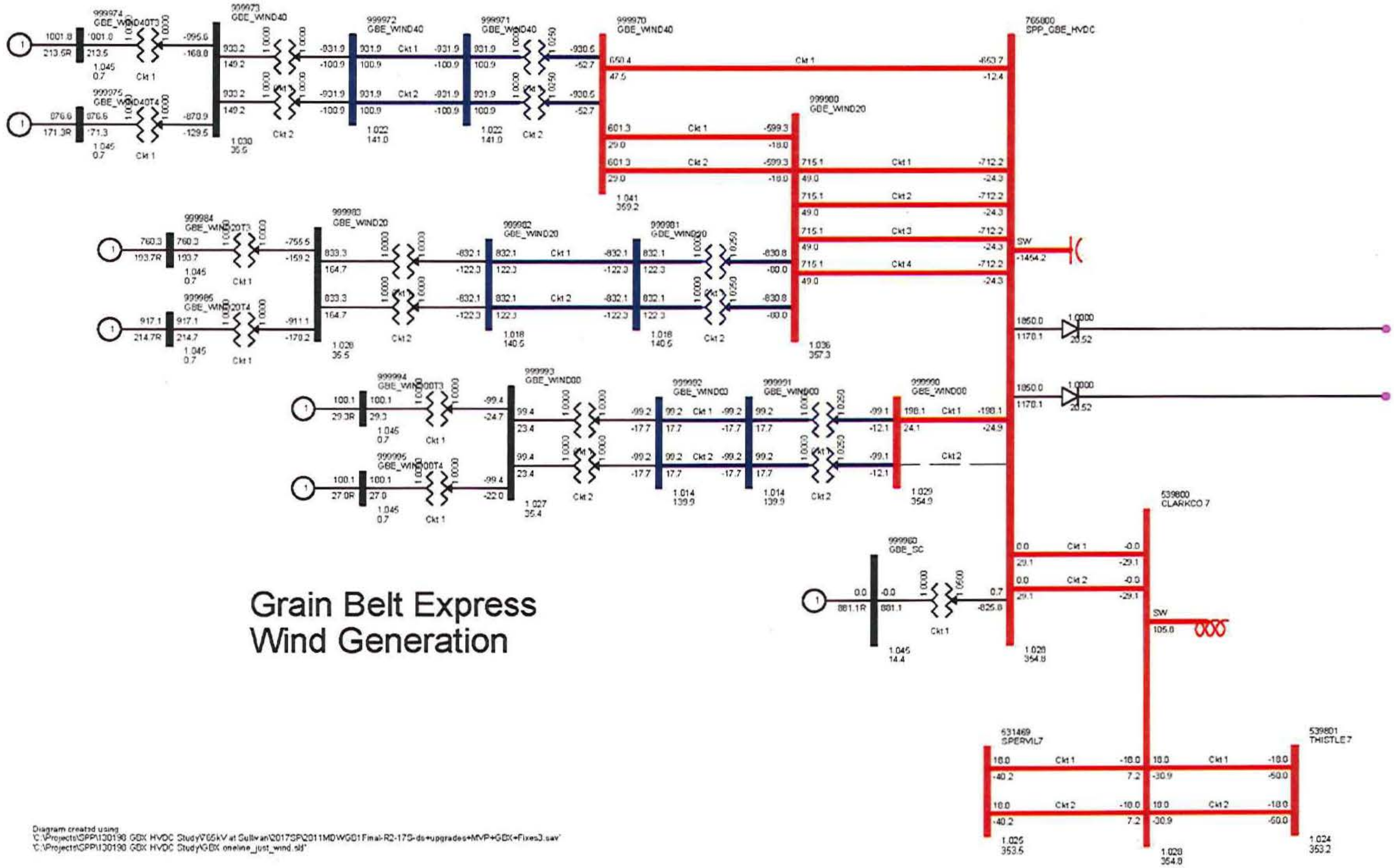


Figure 3-2. Power Flow One-line of GBX Wind Generation – 2017 Summer Peak

3.3 *Monitored Facilities*

Generators and transmission voltages were monitored in the following areas:

Table 3-1. Areas Monitored

AREA	NAME	AREA	NAME
523	GRDA	540	GMO
524	OKGE	541	KCPL
526	SPS	542	KACY
531	MIDW	640	NPPD
534	SUNC	330	AECI
536	WERE	351	EES

Additional generators were monitored near the AEP Sullivan and AMMO Palmyra rectifier stations, as listed in Table 3-2 and Table 3-3, respectively.

A selection of plots of voltage, frequency, rotor angle and speed from the HVDC project generation and across the SPP footprint were selected as the default plots provided in the appendices.

Table 3-2. Additional Generators Monitored Near Sullivan

Station	Buses	Area
Rockport	243442 - 243443	205 AEP
Petersburg	254811-254814	216 IPL
Gibson	251861-251865	208 DEM
Wheatland	251897-251900	208 DEM
Merom	248773	207 HE
Clifty Ck	248000	206 OVEC
Trimble Co	324034 - 324041	363 LGEE
Cayuga	251849 - 251850	208 DEM
Amos	242891 - 242893	205 AEP
Mountaineer	242894	205 AEP
Mitchel	243188 - 243189	205 AEP
Muskingum	242940	205 AEP
Lawrenceburg	243226	205 AEP
Tanner	243233	205 AEP
Cook	243440 - 243441	205 AEP
Conesville	243622	205 AEP
Big Sandy	243763 - 243764	205 AEP
Killen	253038	209 DAY
Stuart	253077	209 DAY

Table 3-3. Additional Generators Monitored Near Palmyra

Station	Buses	Area
Audrain	344061 - 344063	356 AMMO
Callaway	344225	356 AMMO
Kinmundy	344876	356 AMMO
Labody	344894 - 344895	356 AMMO
Meramad	345132 - 345156	356 AMMO
Osage	345400	356 AMMO
Peno Creek	345441	356 AMMO
Rush Island	345670	356 AMMO
Sioux	345756 - 345765	356 AMMO
Venice	345882	356 AMMO
Raccoon Ck	345994	356 AMMO
Goose Creek	345998	356 AMMO
Keokuk	344863	356 AMMO
Alsey	346516	357 AMIL
Avena	346573	357 AMIL
Coffeen	346897	357 AMIL
Gibson City	347112	357 AMIL
Grand Tower	347170	357 AMIL
Holland Energy	347231	357 AMIL
Hutsonville	347271	357 AMIL
RELU	347819	357 AMIL
Newton	347832	357 AMIL
Clinton	349101	357 AMIL
Vermilion	349109	357 AMIL
Wood River	349115	357 AMIL
Havana	349121	357 AMIL
Tilton	349122	357 AMIL
Baldwin	349126	357 AMIL
Prairie State	349129	357 AMIL
Edwards	349632	357 AMIL
Duck Ck	349633	357 AMIL
Railsplitter	349724	357 AMIL

3.4 Performance Evaluation Methods

The faults shown in Table 3-4 were simulated in this study. This list includes all faults from the PTI report plus some faults at 230 kV and lower voltage levels added at the request of transmission owner Sunflower Electric Power Corporation (SEPC).

Some N-1-1 and N-2 faults were also added to the list. Since both ends of the Clark Co – Spearville 345 kV lines were tested in the original study (FLT12A, FLT12B), a new FLT11B was added to the existing FLT11A so that the Clark Co – Thistle 345 kV lines received the same treatment. The solutions to these faults were tested as pre-fault wind reductions (FLT11C, FLT12C). N-2 faults (aka NERC Category C5) were added for these lines as well (FLT11D, FLT11E, FLT12D).

Simulation channels of voltages, frequencies, rotor angles, and speed deviation from areas covering the entire SPP footprint were selected as the default plot for each disturbance simulation.

All generators were reviewed for stability and tripping. Transmission bus voltages checked against the SPP requirement of 70% to 120% after fault clearing.

Table 3-4. Fault Definitions

No	Description	kV
	3-phase faults with normal clearing	
1	At Clark Co 765800, both poles are blocked	345
2	At Clark Co 765800, one pole is recovered	345
3	At Clark Co 765800, both poles are recovered	345
4	At Sullivan 765773, both poles are blocked	345
5	At Sullivan 765773, one pole is recovered	345
6	At Sullivan 765773, both poles are recovered	345
7	At Palmyra 765772, both poles are blocked	345
8	At Palmyra 765772, one pole is recovered	345
9	At Palmyra 765772, both poles are recovered	345
10	the Palmyra inverter of the recovered pole is still	345
11	Clark Co 539800 - Thistle 539801	345
12	Clark Co 539800 - Spearville 531469	345
13	Thistle 539801 - Wichita 532796	345
14	Thistle 539801 - Woodward 515375	345
15	Woodward 515375 - Tatonga 515407	345
16	Spearville 531469 - Holcomb 531449	345
17	Spearville 531469 - Post Rock 530583	345
18	Spearville 345/230 kV TF (531469 - 539695)	345/230

No	Description	kV
19	Spearville 539695 - Mullergren 539679	230
20	Post Rock 530583 - Axtell 640065	345
21	Holcomb 531449 - Finney 523853	345
22	Holcomb 531449 - Setab 531465	345
23	Finney 523853 - Hitchland 523080	345
24	Finney 523853 - Lamar 599950	345
25	Setab 531465 - Mingo 531451	345
26	Mingo 531451 - Red Willow 640325	345
27	Sullivan 3wnd TF (243210-765773-999920)	765/345
28	Sullivan 765/345 kV TF (243210 - 243213)	765/345
29	Sullivan 243210 - Rockport 243209	765
30	Breed 243213 - Casey 346809	345
31	Breed 243213 - Darwin 243216	345
32	Breed 243213 - Dequine 243217	345
33	Breed 243213 - Wheat 254539	345
34	Rockport 243209 - Jefferson 243208	765
35	Palmyra 765772 - Palmyra tap 345435	345
36	Palmyra Tap 345435 - Sub T 636645	345
37	Palmyra Tap 345435 - Palmyra 345436	345
38	Palmyra Tap 345435 - Adair 344000	345
39	Palmyra Tap 345435 - Spencer 345992	345
40	Palmyra Tap 345435 - Se Quincy 347010	345
	SLG faults with protection failure	
41	Clark Co 539800 - Thistle 539801	345
42	Clark Co 539800 - Spearville 531469	345
43	Thistle 539801 - Wichita 532796	345
44	Thistle 539801 - Woodward 515375	345
45	Woodward 515375 - Tatonga 515407	345
46	Spearville 531469 - Holcomb 531449	345
47	Spearville 531469 - Post Rock 530583	345
48	Spearville 345/230 kV TF (531469 - 539695)	345/230
49	Spearville 539695 - Mullergren 539679	230
50	Post Rock 530583 - Axtell 640065	345
51	Holcomb 531449 - Finney 523853	345
52	Holcomb 531449 - Setab 531465	345
53	Finney 523853 - Hitchland 523080	345
54	Finney 523853 - Lamar 599950	345
55	Setab 531465 - Mingo 531451	345

No	Description	kV
56	Mingo 531451 - Red Willow 640325	345
57	Sullivan 3wnd TF (243210-765773-999920)	765/345
58	Sullivan 765/345 kV TF (243210 - 243213)	765/345
59	Sullivan 243210 - Rockport 243209	765
60	Breed 243213 - Casey 346809	345
61	Breed 243213 - Darwin 243216	345
62	Breed 243213 - Dequine 243217	345
63	Breed 243213 - Wheat 254539	345
64	Rockport 243209 - Jefferson 243208	765
65	Palmyra 765772 - Palmyra tap 345435	345
66	Palmyra Tap 345435 - Sub T 636645	345
67	Palmyra Tap 345435 - Palmyra 345436	345
68	Palmyra Tap 345435 - Adair 344000	345
69	Palmyra Tap 345435 - Spencer 345992	345
70	Palmyra Tap 345435 - Se Quincy 347010	345
	SLG faults with stuck breaker	
71	Fault at Rectifier, block the pole and trip line to collector system	345
72	Fault at Sullivan, trip 3wnd and 2wnd transformers	765/345
73	Fault at Palmyra Tap, trip lines to inverter station and to Palmyra	345
	Faults Added by Sunflower	
74	Mullergren 539679 - Circle 532871, 3-phase	230
75	Mullergren 539679 - Circle 532871, 1-phase delayed	230
76	Pile 531432 - Dobson 531419, 3-phase	115
77	Pile 531432 - Dobson 531419, 1-phase delayed	115
78	Holcomb transformer 531449-531448, 3-phase	345/115
79	Holcomb transformer 531449-531448, 1- phase delayed	345/115
80	Harper 539668 - Milan Tap 539675 - Clearwater 533036, 3-phase	138
81	Harper 539668 - Milan Tap 539675 - Clearwater 533036, 1- phase delayed	138
	N-1-1 and N-2, 3 phase fault with normal clearing	
11A	Prior outage of Clark Co - Thistle #1, fault on #2	345
11B	Prior outage of Thistle - Clark Co #1, fault on #2	345
11C	Prior outage of some GBX wind generation and Clark Co - Thistle #1, fault on #2	345
11D	Clark Co 539800 - Thistle 539801 double circuit	345
11E	Thistle 539801 - Clark Co 539800 double circuit	345
12A	Prior outage of Spearville - Clark Co #1, fault on #2	345

No	Description	kV
12B	Prior outage of Clark Co - Spearville #1, fault on #2	345
12C	Prior outage of some GBX wind generation and Clark Co - Spearville #1, fault on #2	345
12D	Clark Co 539800 - Spearville 531469 double circuit	345
17A	Prior outage of Spearville - Holcomb, fault on Spearville - Post Rock	345

4. Results and Observations

4.1 Stability Analysis Results

Table 4-1 summarizes the results of the initial simulations. Discussion of specific results follows the table.

Table 4-1. Summary of Stability Results

No	Description	2017 LL	2017 SP	2022 SP
	3-phase faults with normal clearing			
1	At Clark Co 765800, both poles are blocked	ok	ok	ok
2	At Clark Co 765800, one pole is recovered	ok	ok	ok
3	At Clark Co 765800, both poles are recovered	ok	ok	ok
4	At Sullivan 765773, both poles are blocked	ok	ok	ok
5	At Sullivan 765773, one pole is recovered	ok	ok	ok
6	At Sullivan 765773, both poles are recovered	ok	ok	ok
7	At Palmyra 765772, both poles are blocked	ok	ok	ok
8	At Palmyra 765772, one pole is recovered	ok	ok	ok
9	At Palmyra 765772, both poles are recovered	ok	ok	ok
10	the Palmyra inverter of the recovered pole is still	ok	ok	ok
11	Clark Co 539800 - Thistle 539801	ok	ok	ok
12	Clark Co 539800 - Spearville 531469	ok	ok	ok
13	Thistle 539801 - Wichita 532796	ok	ok	ok
14	Thistle 539801 - Woodward 515375	ok	ok	ok
15	Woodward 515375 - Tatonga 515407	ok	ok	ok
16	Spearville 531469 - Holcomb 531449	ok	ok	ok
17	Spearville 531469 - Post Rock 530583	ok	ok	ok
18	Spearville 345/230 kV TF (531469 - 539695)	ok	ok	ok
19	Spearville 539695 - Mullergren 539679	ok	ok	ok
20	Post Rock 530583 - Axtell 640065	ok	ok	ok
21	Holcomb 531449 - Finney 523853	ok	ok	ok
22	Holcomb 531449 - Setab 531465	ok	ok	ok
23	Finney 523853 - Hitchland 523080	ok	ok	ok
24	Finney 523853 - Lamar 599950	ok	ok	ok
25	Setab 531465 - Mingo 531451	ok	ok	ok
26	Mingo 531451 - Red Willow 640325	ok	ok	ok
27	Sullivan 3wnd TF (243210-765773-999920)	ok	ok	ok
28	Sullivan 765/345 kV TF (243210 - 243213)	ok	ok	ok

No	Description	2017 LL	2017 SP	2022 SP
29	Sullivan 243210 - Rockport 243209	ok	ok	ok
30	Breed 243213 - Casey 346809	ok	ok	ok
31	Breed 243213 - Darwin 243216	ok	ok	ok
32	Breed 243213 - Dequine 243217	ok	ok	ok
33	Breed 243213 - Wheat 254539	ok	ok	ok
34	Rockport 243209 - Jefferson 243208	ok	ok	ok
35	Palmyra 765772 - Palmyra tap 345435	ok	ok	ok
36	Palmyra Tap 345435 - Sub T 636645	ok	ok	ok
37	Palmyra Tap 345435 - Palmyra 345436	ok	ok	ok
38	Palmyra Tap 345435 - Adair 344000	ok	ok	ok
39	Palmyra Tap 345435 - Spencer 345992	ok	ok	ok
40	Palmyra Tap 345435 - Se Quincy 347010	ok	ok	ok
	SLG faults with protection failure			
41	Clark Co 539800 - Thistle 539801	ok	ok	ok
42	Clark Co 539800 - Spearville 531469	ok	ok	ok
43	Thistle 539801 - Wichita 532796	ok	ok	ok
44	Thistle 539801 - Woodward 515375	ok	ok	ok
45	Woodward 515375 - Tatonga 515407	ok	ok	ok
46	Spearville 531469 - Holcomb 531449	ok	ok	ok
47	Spearville 531469 - Post Rock 530583	ok	ok	ok
48	Spearville 345/230 kV TF (531469 - 539695)	ok	ok	ok
49	Spearville 539695 - Mullergren 539679	ok	ok	ok
50	Post Rock 530583 - Axtell 640065	ok	ok	ok
51	Holcomb 531449 - Finney 523853	ok	ok	ok
52	Holcomb 531449 - Setab 531465	ok	ok	ok
53	Finney 523853 - Hitchland 523080	ok	ok	ok
54	Finney 523853 - Lamar 599950	ok	ok	ok
55	Setab 531465 - Mingo 531451	ok	ok	ok
56	Mingo 531451 - Red Willow 640325	ok	ok	ok
57	Sullivan 3wnd TF (243210-765773-999920)	ok	ok	ok
58	Sullivan 765/345 kV TF (243210 - 243213)	ok	ok	ok
59	Sullivan 243210 - Rockport 243209	ok	ok	ok
60	Breed 243213 - Casey 346809	ok	ok	ok
61	Breed 243213 - Darwin 243216	ok	ok	ok
62	Breed 243213 - Dequine 243217	ok	ok	ok
63	Breed 243213 - Wheat 254539	ok	ok	ok
64	Rockport 243209 - Jefferson 243208	ok	ok	ok

No	Description	2017 LL	2017 SP	2022 SP
65	Palmyra 765772 - Palmyra tap 345435	ok	ok	ok
66	Palmyra Tap 345435 - Sub T 636645	ok	ok	ok
67	Palmyra Tap 345435 - Palmyra 345436	ok	ok	ok
68	Palmyra Tap 345435 - Adair 344000	ok	ok	ok
69	Palmyra Tap 345435 - Spencer 345992	ok	ok	ok
70	Palmyra Tap 345435 - Se Quincy 347010	ok	ok	ok
	SLG faults with stuck breaker			
71	Fault at Rectifier, block the pole and trip line to collector system	ok	ok	ok
72	Fault at Sullivan, trip 3wnd and 2wnd transformers	ok	ok	ok
73	Fault at Palmyra Tap, trip lines to inverter station and to Palmyra	ok	ok	ok
	Faults Added by Sunflower			
74	Mullergren - Circle, 3-phase	ok	ok	ok
75	Mullergren - Circle, 1-phase delayed	ok	ok	ok
76	Pile - Dobson, 3-phase	ok	ok	ok
77	Pile - Dobson, 1-phase delayed	ok	ok	ok
78	Holcomb transformer, 3-phase	ok	ok	ok
79	Holcomb transformer, 1- phase delayed	ok	ok	ok
80	Harper - Milan Tap - Clearwater, 3-phase	ok	ok	ok
81	Harper - Milan Tap - Clearwater, 1- phase delayed	ok	ok	ok
	N-1-1 and N-2, 3 phase fault with normal clearing			
11A	Prior outage of Clark Co - Thistle #1, fault on #2	unstable	unstable	unstable
11A _voltcont	Prior outage of Clark Co - Thistle #1, fault on #2 Trip some wind generation	Ok if trip 877 MW	Ok if trip 760 MW	Ok if trip 760 MW
11B	Prior outage of Thistle - Clark Co #1, fault on #2	unstable	unstable	unstable
11B _voltcont	Prior outage of Thistle - Clark Co #1, fault on #2 Trip some wind generation	Ok if trip 1637 MW	Ok if trip 1637 MW	Ok if trip 1637 MW
11C	Prior outage of some GBX wind generation and Clark Co - Thistle #1, fault on #2	Ok if trip 877 MW	Ok if trip 877 MW	Ok if trip 877 MW
11D	Clark Co - Thistle double circuit	unstable	unstable	unstable
11D _voltcont	Clark Co - Thistle double circuit Trip some wind generation	Ok if trip 877 MW	Ok if trip 877 MW	Ok if trip 877 MW
11E	Thistle - Clark Co double circuit	unstable	unstable	unstable
11E _voltcont	Thistle - Clark Co double circuit Trip some wind generation	Ok if trip 1637 MW	Ok if trip 1637 MW	Ok if trip 1637 MW
12A	Prior outage of Spearville - Clark Co #1, fault on #2	ok	ok	ok

No	Description	2017 LL	2017 SP	2022 SP
12B	Prior outage of Clark Co - Spearville #1, fault on #2	unstable	unstable	unstable
12B _voltcont	Prior outage of Clark Co - Spearville #1, fault on #2 Trip some wind generation	Ok if trip 877 MW	Ok if trip 877 MW	Ok if trip 877 MW
12C	Prior outage of some GBX wind generation and Clark Co - Spearville #1, fault on #2	Ok if trip 877 MW	Ok if trip 877 MW	Ok if trip 877 MW
12D	Clark Co - Spearville double circuit	unstable	unstable	unstable
12D _voltcont	Clark Co - Spearville double circuit Trip some wind generation	Ok if trip 877 MW	Ok if trip 877 MW	Ok if trip 877 MW
17A	Prior outage of Spearville - Holcomb, fault on Spearville - Post Rock	ok	ok	ok

4.2 Discussion of Notable Results

4.2.1 Faults near SPP Clark County 345 kV Station

All of the NERC Category B faults in SPP were stable. Some of the NERC Category C faults were unstable, including the N-1-1 (aka NERC Category C3) faults on the Clark Co. – Spearville 345 kV lines (FLT12A, FLT12B) and the Clark Co. – Thistle 345 kV lines (FLT11A, FLT11B). If one of the lines is out of service and the parallel line has a fault, the GBX wind generators trip on over-frequency (see plot of FLT11A in Figure 4-1). To fix this problem, the PTI report proposes tripping some of the wind generation (760-877 MW) at the same time as the faulted line. This solution is confirmed to work and allows the remaining GBX wind generation to stay on-line and stable (Figure 4-2). However, generation tripping will require a Special Protection System (SPS) that may not be acceptable to SPP or the transmission owner.

Another option is to reduce wind generation after the first contingency occurs but before the second contingency. This option was tested in PSS/E as FLT11C and FLT12C, and the results were stable but without the need for an SPS (Figure 4-3).

If the parallel Clark Co. – Spearville 345 kV lines share towers, or if the parallel Clark Co. – Thistle 345 kV lines share towers, then NERC Category C5 will have to be considered as well. In this case, there is no option to reduce wind generation and HVDC schedule between the two line trips. Consideration of Category C5 would bring back the need for post-fault generation tripping. Simulations were run (FLT11D, FLT11E, and FLT12D) that demonstrated the generation tripping solution works for the N-2 contingencies just as well as for the N-1-1 contingencies. However, if an SPS is not acceptable to SPP, then a new transmission line or other major upgrade may be needed.

The original study did not simulate the fault at Thistle for the N-1-1 outage of the Clark Co. – Thistle 345 kV lines. When that fault was tested in this study (FLT11B), more generation tripping was required than for the other faults – 1637 MW. Since a fault can occur anywhere along a line, the largest amount of tripping found while testing faults at both ends will need to be used.

In the original simulations, the HVDC power schedule did not always follow the over-frequency tripping of GBX wind generation. In the actual equipment, HVDC power will need to follow the wind power, at least in the steady state, if not faster. One possibility is for the HVDC control system to continually adjust its power schedule to maintain zero flow on the lines connecting to SPP. This could include active power flow, reactive power flow, or both. The speed of this control will have to be agreed to by Clean Line, SPP, and the local transmission utility. A faster control will reduce inadvertent flows and impacts on the SPP system.

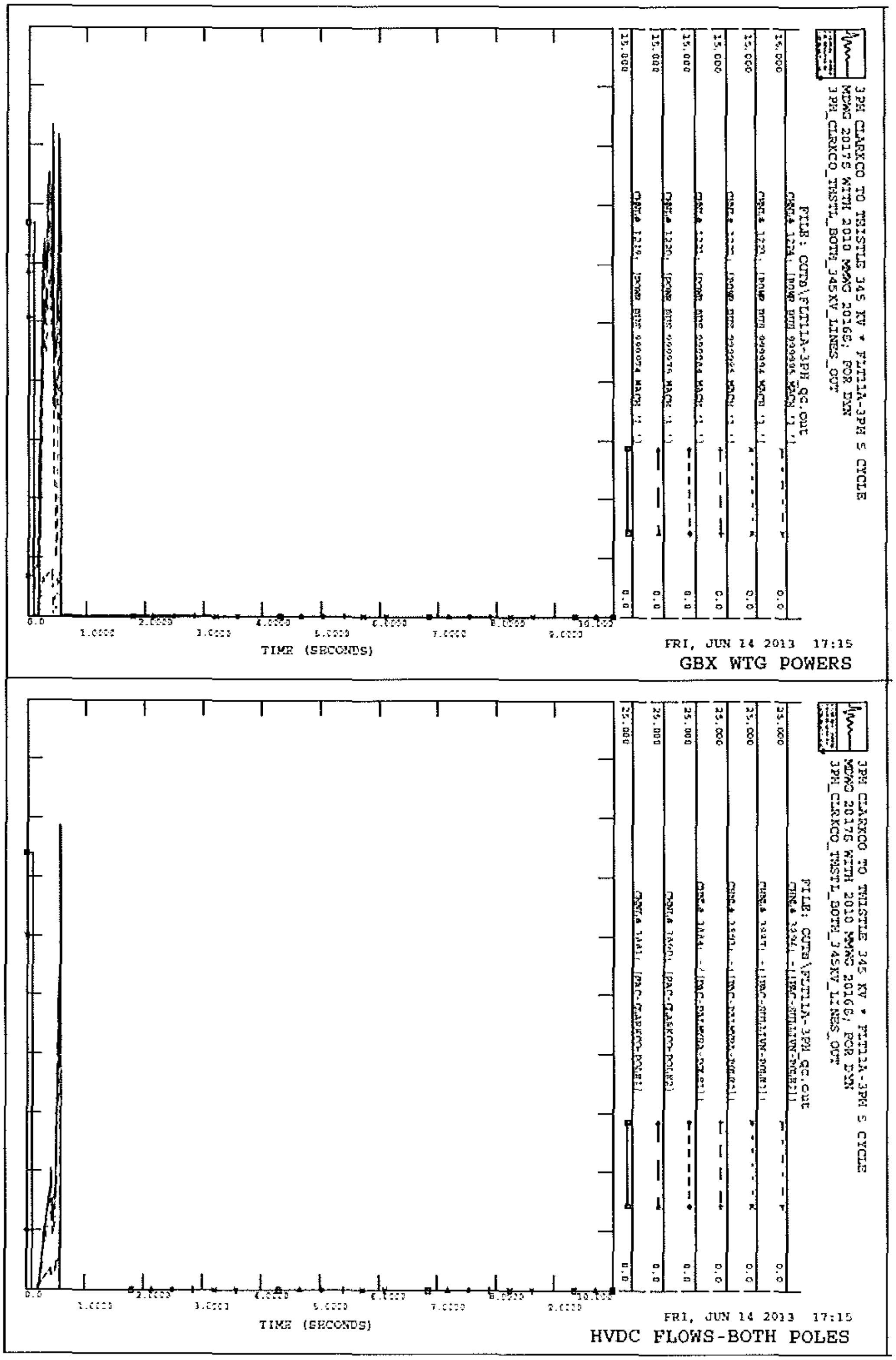


Figure 4-1. Wind and HVDC Powers for FLT11A, 3ph fault on Clark Co – Thistle 345 #1 with prior outage of #2

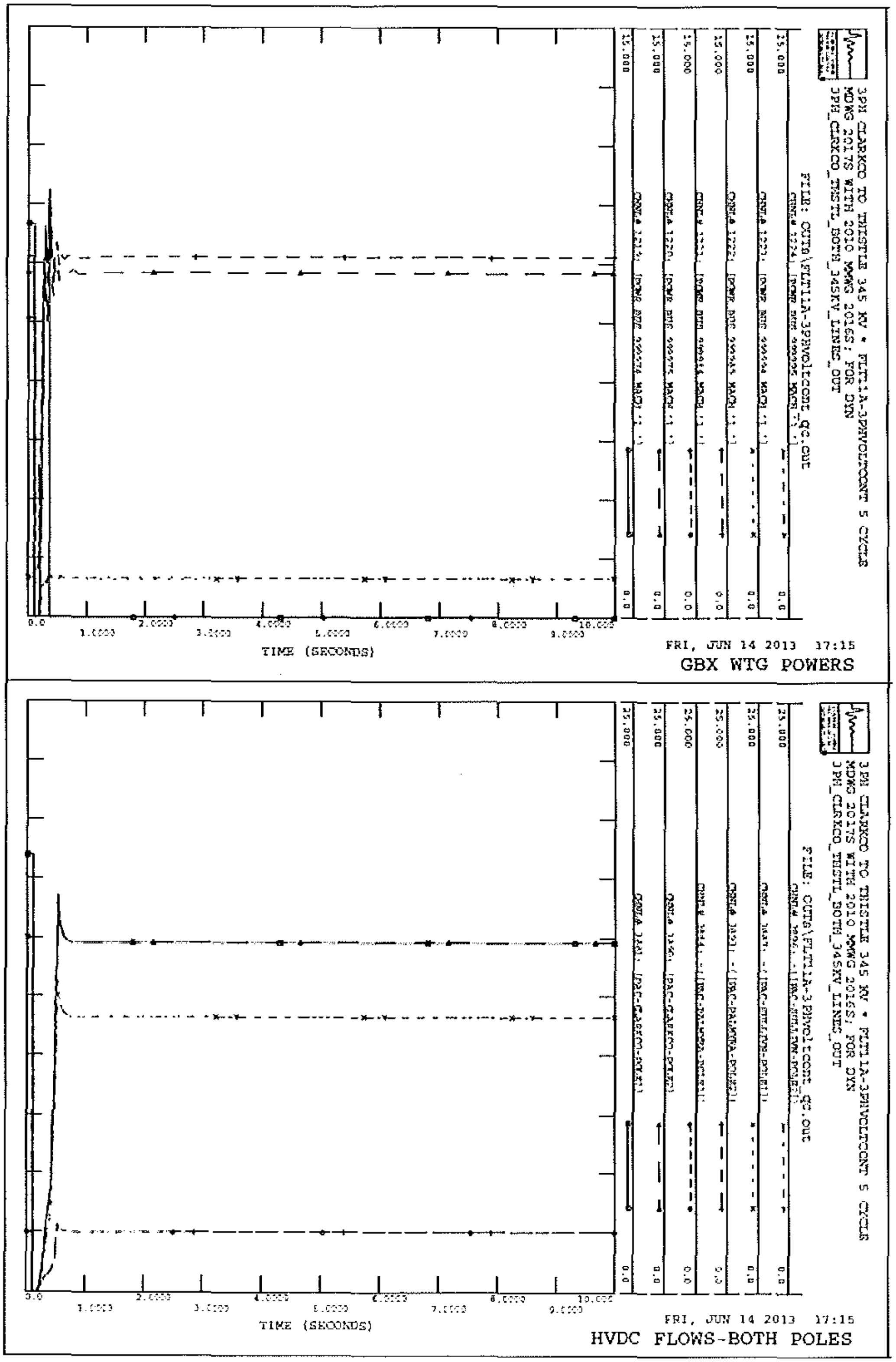


Figure 4-2. Wind and HVDC Powers for FLT11A_voltcont, 3ph fault on Clark Co – Thistle 345 #1 with prior outage of #2, trip some wind generation post-fault

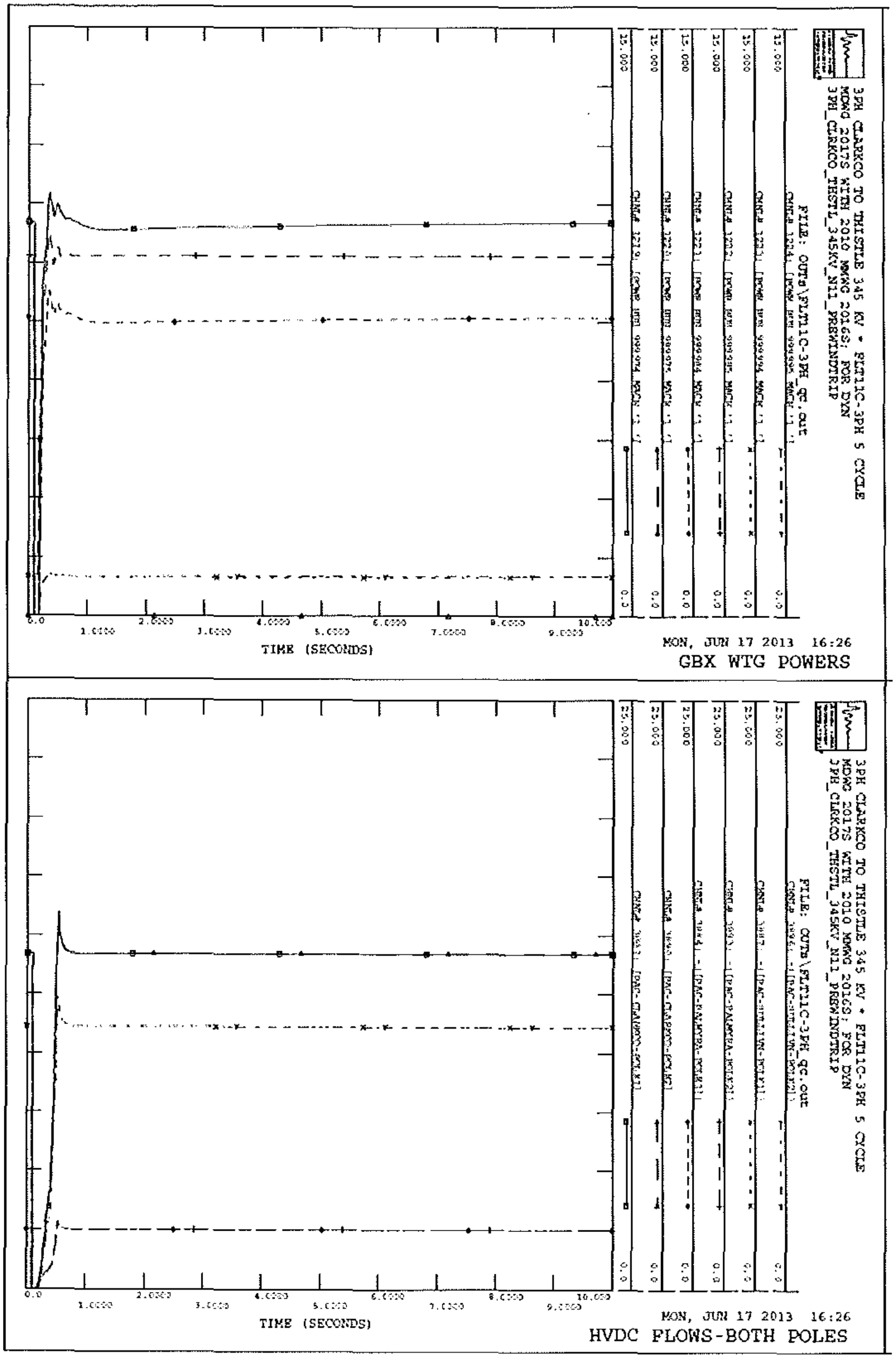


Figure 4-3. Wind and HVDC Powers for FLT11C, 3ph fault on Clark Co – Thistle 345 #1 with prior outage of #2, trip some wind generation PRE-fault

4.2.2 Faults near SPP Clark County 345 kV Station – New POI

The GBX project developer notified SPP of a desire to change the POI to a point 14 miles from Clark Co on the 345 kV lines to Spearville. Section 4.2.1 showed that the critical faults in SPP are the N-1-1 and N-2 faults around the POI. The critical faults were updated and repeated for the new POI location. Faults that were previously simulated at Clark Co, which was the POI for the initial analysis, were moved to the new GBX POI. Faults at Spearville and Thistle were left at those buses. Results are summarized in Table 4-2.

Most of the results are the same as with the previous POI. The most notable difference is that faults 11A and 11D are stable **in the 2017SP case** with the new POI (but still unstable in the 2017LL and 2022SP cases). Losing the lines toward Thistle may not be quite as severe now that the POI is closer to Spearville. However, while the fault 11A and 11D results are officially stable in the 2017SP case, they are not acceptable. After fault clearing, transmission voltage dips as low as 45% at the Post Rock 345 kV bus (Figure 4-4). The solution to trip up to 877 MW of wind generation following faults 11A and 11D continues to work for the new POI, providing both stability and keeping post-fault voltages above 70% (Figure 4-5).

These results match the results shown in PTI's August 13-14 power point slides, for the same faults. As with the original POI, PTI's slides do not discuss faults at the Thistle end of the Clark Co – Thistle 345 kV lines. In this study, these Thistle faults are shown to require the largest amounts of GBX wind tripping.

Table 4-2. Summary of Stability Results for new POI

No	Description	2017 LL	2017 SP	2022 SP
	N-1-1 and N-2, 3 phase fault with normal clearing			
11A	Prior outage of GBX POI - Clark Co #1, fault on #2	unstable	severe voltage dip	unstable
11A _voltcont	Prior outage of GBX POI - Clark Co #1, fault on #2 Trip some wind generation	Ok if trip 877 MW	Ok if trip 760 MW	Ok if trip 760 MW
11B	Prior outage of Thistle - Clark Co #1, fault on #2	unstable	unstable	unstable
11B _voltcont	Prior outage of Thistle - Clark Co #1, fault on #2 Trip some wind generation	Ok if trip 1637 MW	Ok if trip 1637 MW	Ok if trip 1637 MW
11C	Prior outage of some GBX wind generation and GBX POI - Clark Co #1, fault on #2	Ok if trip 877 MW	Ok if trip 877 MW	Ok if trip 877 MW
11D	GBX POI - Clark Co double circuit	unstable	severe voltage dip	unstable
11D _voltcont	GBX POI - Clark Co double circuit Trip some wind generation	Ok if trip 877 MW	Ok if trip 877 MW	Ok if trip 877 MW
11E	Thistle - Clark Co double circuit	unstable	unstable	unstable
11E _voltcont	Thistle - Clark Co double circuit Trip some wind generation	Ok if trip 1637 MW	Ok if trip 1637 MW	Ok if trip 1637 MW
12A	Prior outage of Spearville - GBX POI #1, fault on #2	ok	ok	ok
12B	Prior outage of GBX POI - Spearville #1, fault on #2	unstable	unstable	unstable
12B _voltcont	Prior outage of GBX POI - Spearville #1, fault on #2 Trip some wind generation	Ok if trip 877 MW	Ok if trip 877 MW	Ok if trip 877 MW
12C	Prior outage of some GBX wind generation and GBX POI - Spearville #1, fault on #2	Ok if trip 877 MW	Ok if trip 877 MW	Ok if trip 877 MW
12D	GBX POI - Spearville double circuit	unstable	unstable	unstable
12D _voltcont	GBX POI - Spearville double circuit Trip some wind generation	Ok if trip 877 MW	Ok if trip 877 MW	Ok if trip 877 MW
17A	Prior outage of Spearville - Holcomb, fault on Spearville - Post Rock	ok	ok	ok

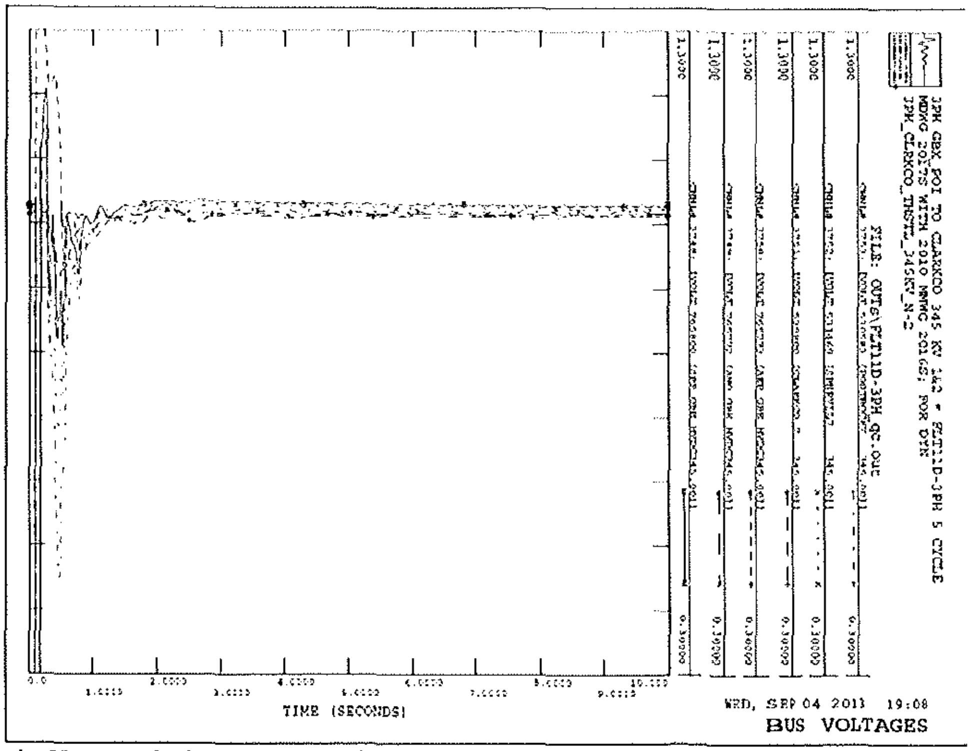


Figure 4-4. Transmission Voltages for FLT11D, 3ph fault on GBX POI – Clark Co 345 #1 and #2 double circuit

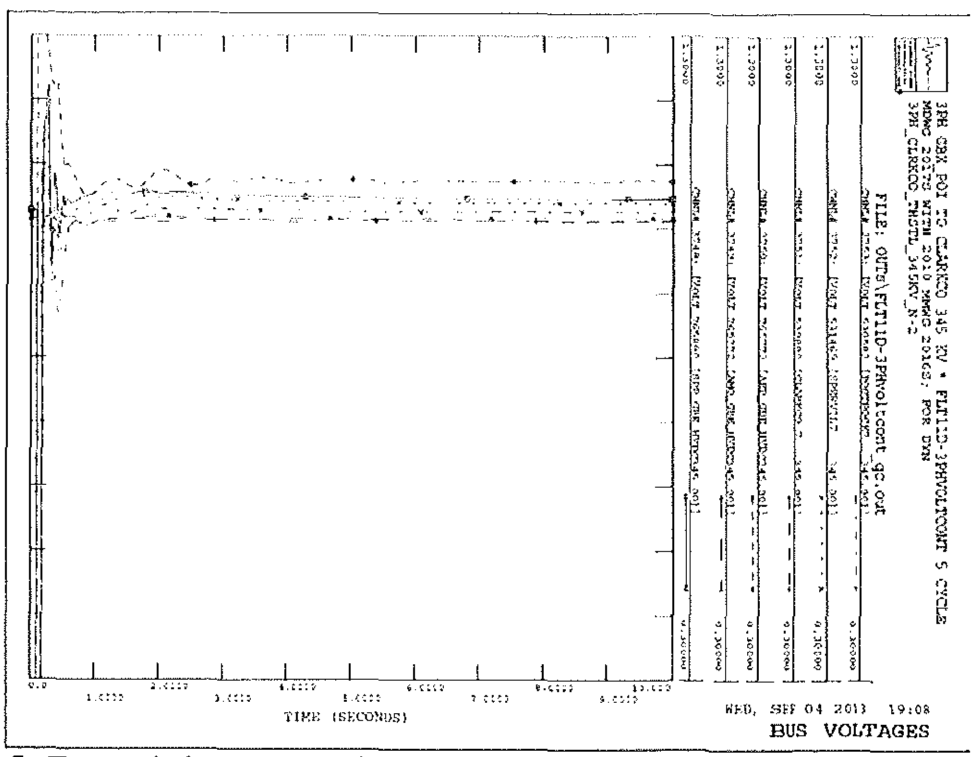


Figure 4-5. Transmission Voltages for FLT11D, 3ph fault on GBX POI – Clark Co 345 #1 and #2 double circuit, trip some wind generation post-fault

4.2.3 Faults near AEP Sullivan 765/345 kV Station

After most of this study work was complete, Clean Line notified SPP that the 765 kV connection option at the AEP Sullivan station should no longer be considered. The 345 kV connection at Sullivan is now the only option considered at the AEP end of the HVDC line. The following discussion applies to the Sullivan 345 kV connection.

The most severe fault near Sullivan was on the Rockport – Jefferson 765 kV line. Loss of this line results in all 2600 MW from the Rockport plant feeding into Sullivan 765 and Breed 345 stations, the same place where 3000 MW is injected from the GBX project. The Rockport generators go unstable and trip off-line in the 2017SP (Figure 4-6) and 2022SP cases. This problem did not show up in the 2017LL case because Rockport was dispatched at a lower level of 1760 MW.

When this contingency was tested in AC power flow on the 2017SP and 2022SP cases, the Newton solution algorithm diverged. Looking at the pre-contingency 2017SP base case with the GBX project, the Rockport – Jefferson 765 kV line is loaded to 3076 MW, beyond its surge impedance loading of 2270 MW. The line is consuming a total of 773 Mvar of reactive power (including 300 Mvar of line shunt reactors) and the Rockport generators are running at a high reactive power output.

The PTI report showed that reducing HVDC power injection at Sullivan to 1500 MW by tripping one pole following the Rockport – Jefferson 765 kV fault allowed the Rockport units to remain stable. This solution was confirmed in dynamics (Figure 4-7) and was also stable in power flow. However, this solution would require an SPS that may not be allowed by AEP. If an SPS is not acceptable, then a major transmission upgrade, such as a new line, may be needed near Sullivan or Rockport, or the project size may need to be reduced.

The 3500 MW injection option at Sullivan was not studied. This scenario will need to be addressed if the project moves forward with its current design.

4.2.4 Faults near AMMO Palmyra Tap 345 kV Station

All faults near the AMMO Palmyra Tap station were stable. The GBX HVDC project only injects 500 MW at this 345 kV station that includes five (5) 345 kV transmission lines. Figure 4-8 shows example plots for a three-phase fault on the Palmyra Tap – Sub T 345 kV transmission line. Voltages are stable and the HVDC recovers to pre-contingency power flows.

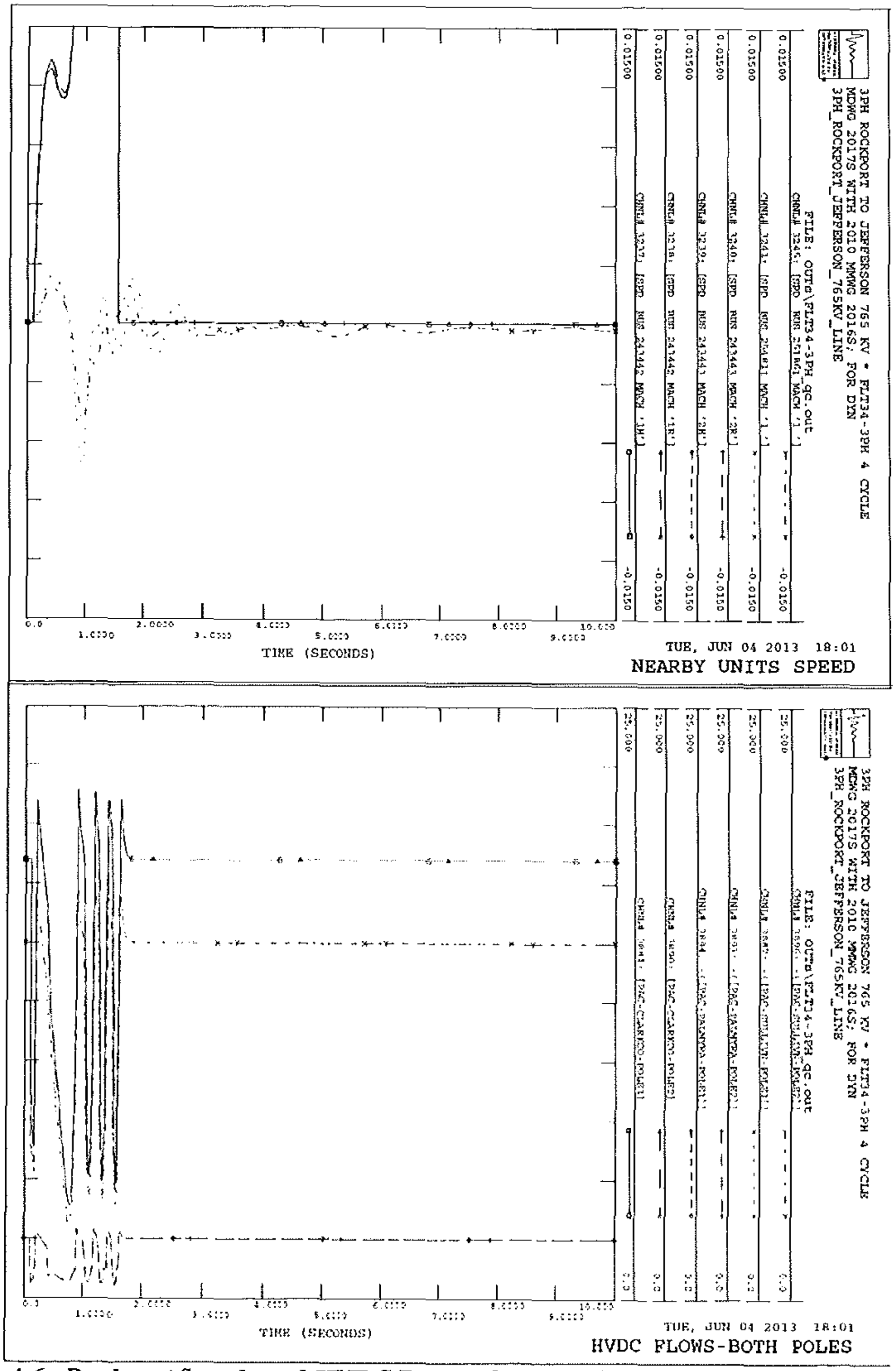


Figure 4-6. Rockport Speeds and HVDC Powers for FLT34, 3ph fault on Rockport – Jefferson 765

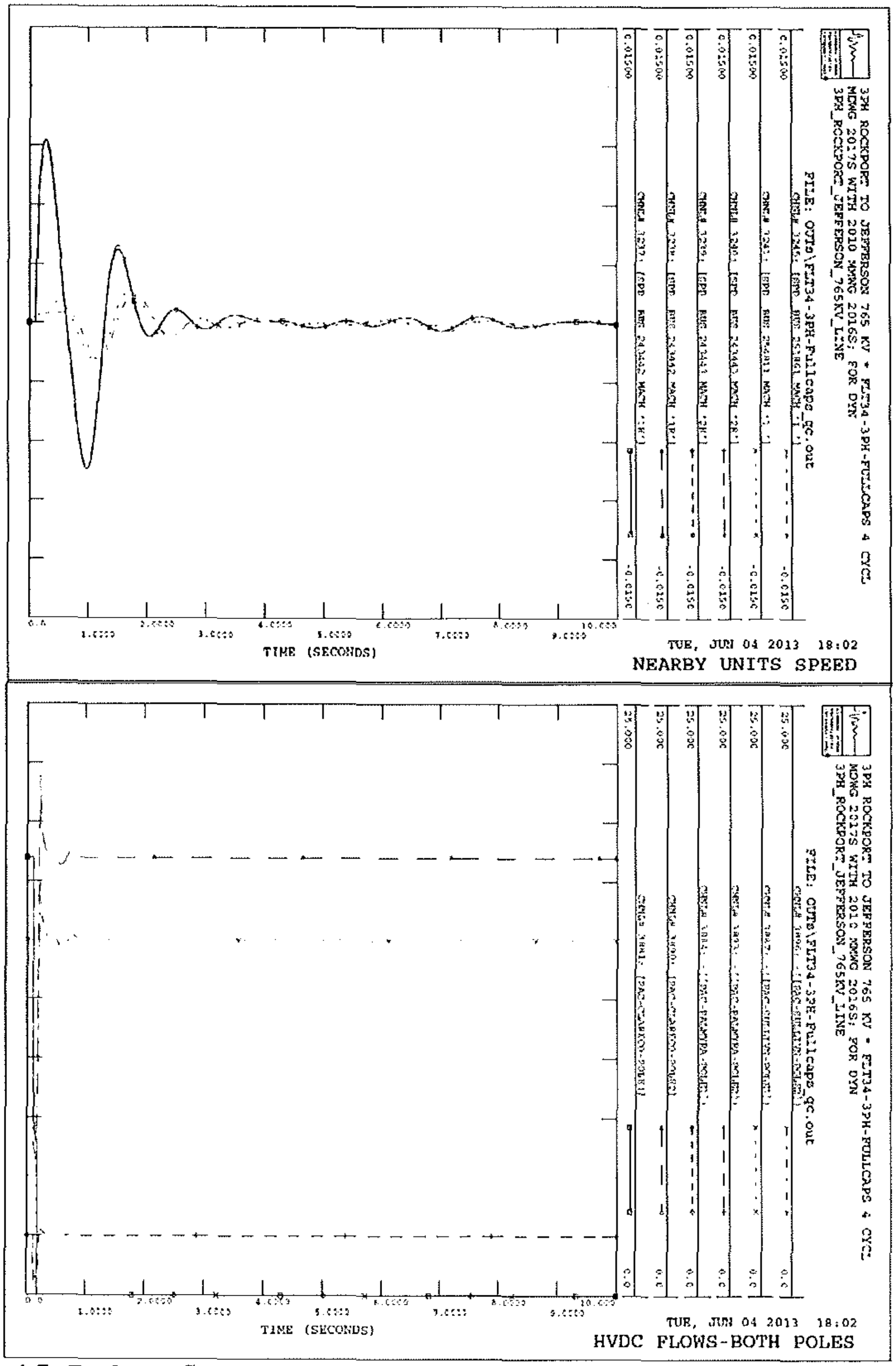


Figure 4-7. Rockport Speeds and HVDC Powers for FLT34, 3ph fault on Rockport – Jefferson 765, tripping one GBX HVDC pole post-fault

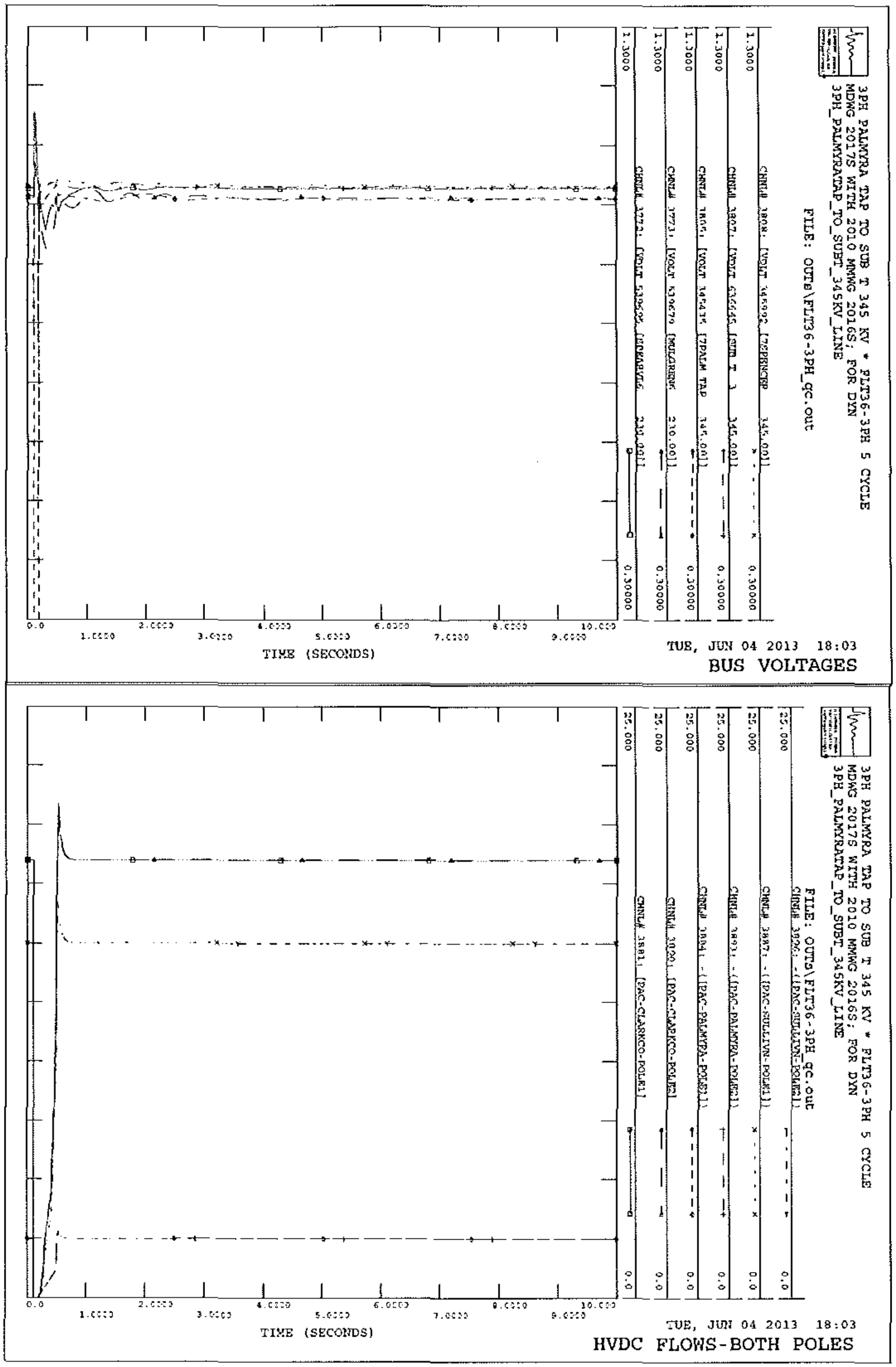


Figure 4-8. Bus Voltages and HVDC Powers for FLT36, 3ph fault on Palmyra Tap – Sub T 345

4.2.5 Both HVDC Poles Blocked

Of particular interest to the existing AC transmission owners and operators is what happens when both HVDC poles are lost. On the SPP side, this results in all GBX wind generation flowing into the SPP AC grid rather than the HVDC lines. The power then flows over the rest of the Eastern Interconnection AC grid to the MISO and PJM loads. The simulations show stable operation following loss of both HVDC poles (Figure 4-9). There is certainly significant power flow onto the SPP transmission network, but the AC grid is able to handle the flow in the short term. The GBX project will still need a control scheme that matches GBX wind generation and HVDC flow as quickly as feasible after an imbalance occurs.

Note however that most wind generation from the SPP interconnection queue is NOT present in the study cases. The current SPP queue contains hundreds of MW of wind plants that plan to connect at or near Clark Co, Spearville, and Thistle 345 kV stations. Stability results could change for the worse if SPP queue generation were included in the analysis.

For faults at the AEP Sullivan and AMMO Palmyra converters resulting in loss of both HVDC poles, simulation results were also stable (Figure 4-10, Figure 4-11).

4.2.6 Transient Voltage Review

After fault clearing, transmission voltages were checked to determine if they fell outside the SPP criteria of 70% to 120%. The previously-discussed unstable faults had many transient voltage violations and are not discussed further in this section.

For stable faults, there were frequent excursions above 120% in the time from fault clearing until the HVDC poles were ramped back up to full power. During this time, the HVDC capacitors were on line but the converters were consuming little to no reactive power. Among the initial fault runs, the highest voltage found was 134.5% at the AEP HVDC converter bus following a fault on the Sullivan-Rockport 765 kV line. The highest voltage seen at an existing bus was 128.7% at Breed 345 for the same fault. During the generation-tripping solutions for some of the N-1-1 faults, up to 136% voltage was seen near the AEP HVDC converter and up to 125.5% near the SPP converter bus.

The GBX project will need to control its reactive power sources and sinks to ensure acceptable voltages. For example, the capacitors can be taken off-line during severe faults that shut down the HVDC converters, and the capacitors can be brought back on in steps as HVDC power is ramped back up.

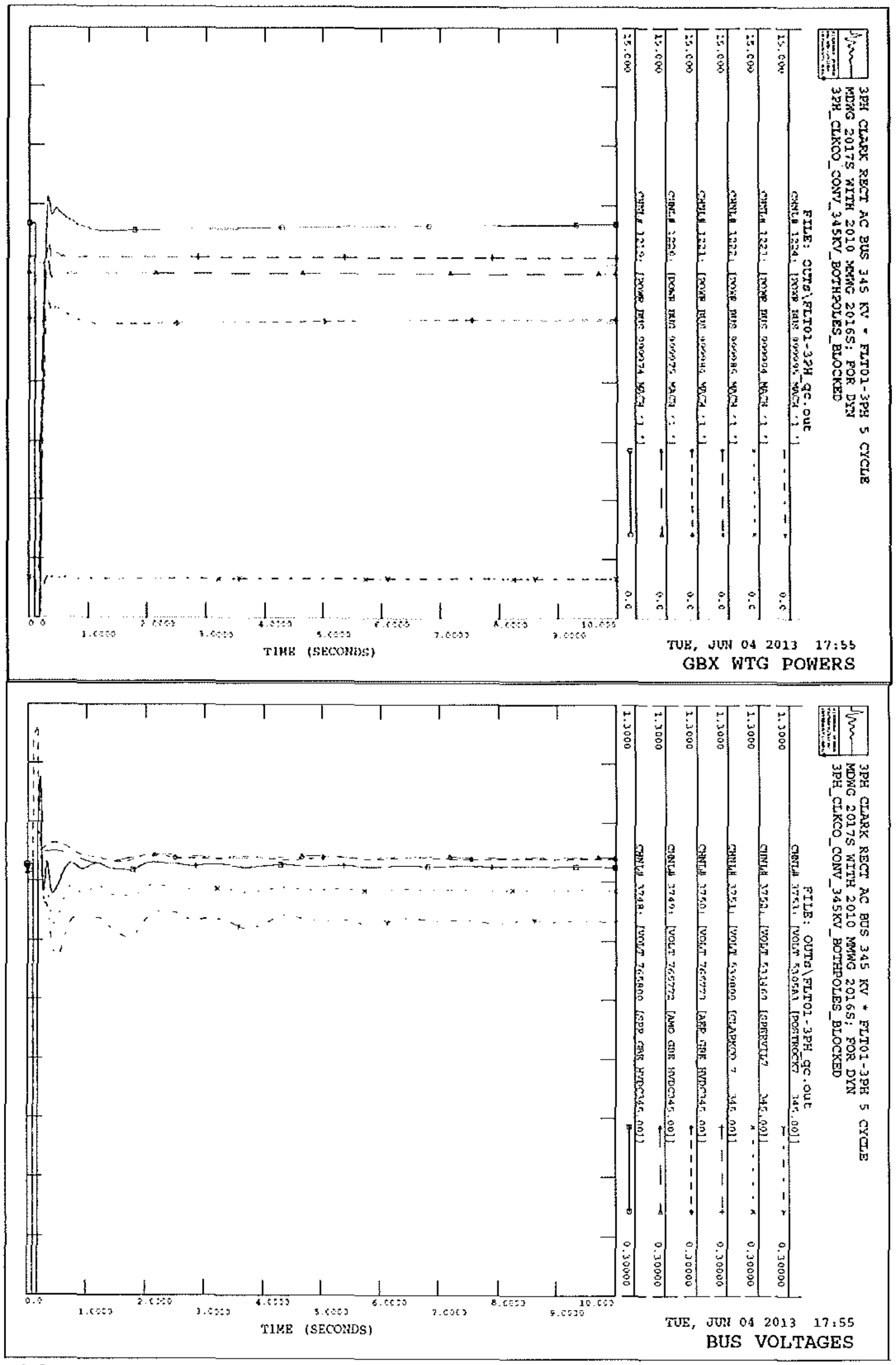


Figure 4-9. GBX Wind Power and Bus Voltages for FLT01, 3ph fault at GBX SPP converter AC bus, tripping both GBX HVDC poles

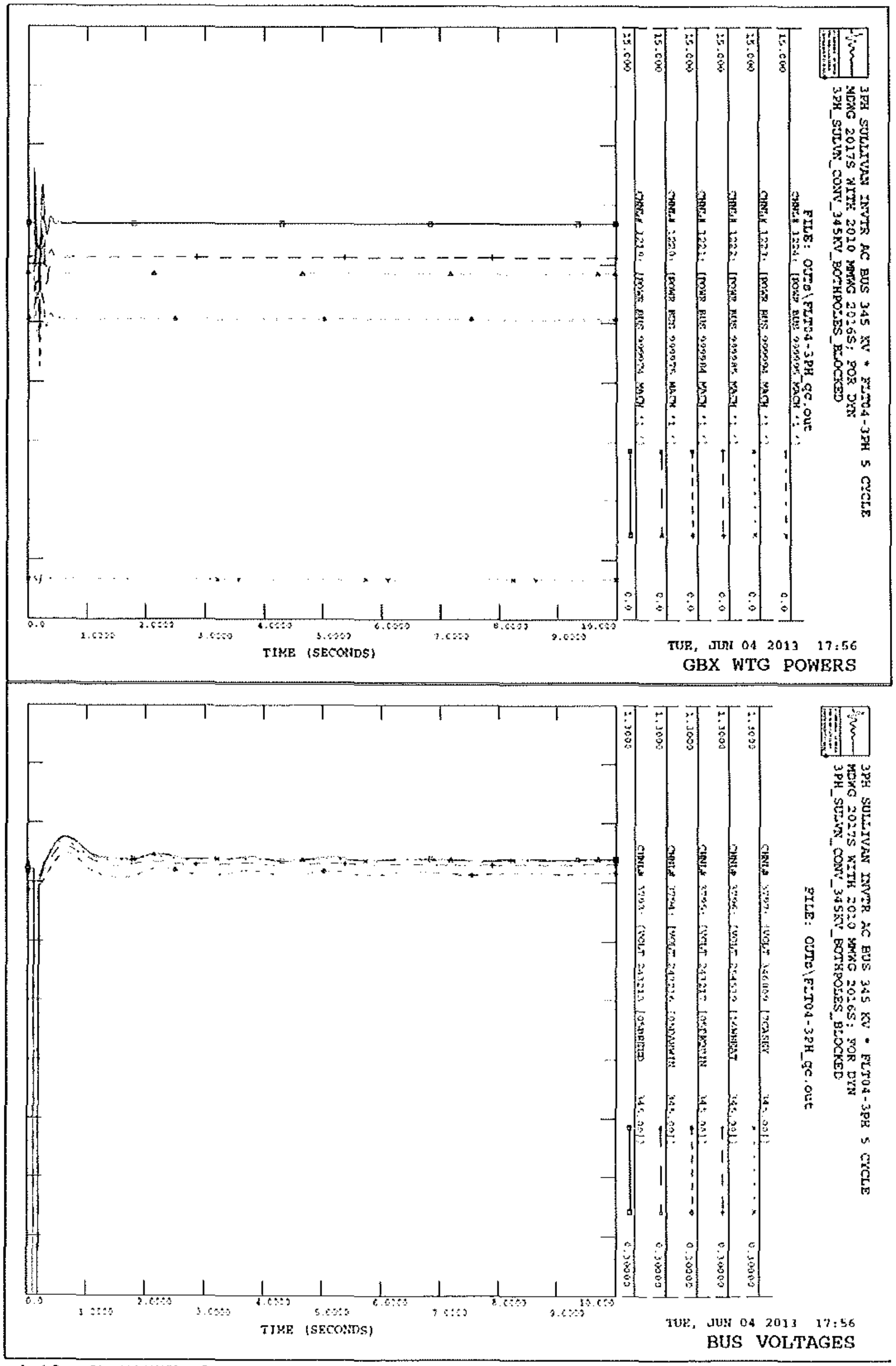


Figure 4-10. GBX Wind Power and Bus Voltages for FLT04, 3ph fault at GBX AEP converter AC bus, tripping both GBX HVDC poles

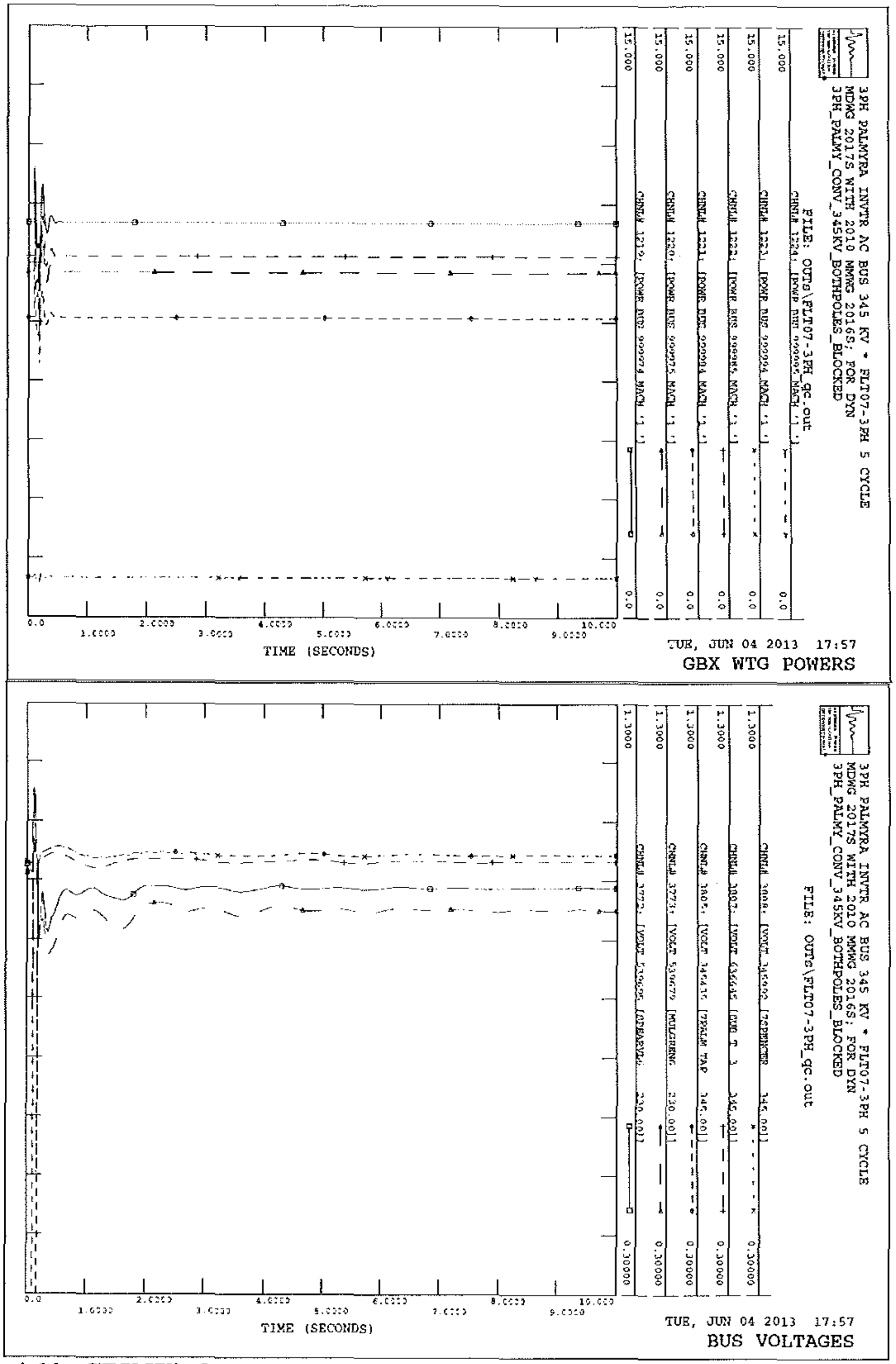


Figure 4-11. GBX Wind Power and Bus Voltages for FLT07, 3ph fault at GBX Palmyra converter AC bus, tripping both GBX HVDC poles

4.3 General Review of the Previous Report

Part of the scope of this project was to review the report created by the developer's consultant. The March 2013 report from Siemens PTI is well-written and describes the problems found and proposed solutions to fix those problems. A few comments on that report and study are as follows:

Conditions Analyzed

The analysis included three-phase faults with normal clearing and single-line-to-ground faults with delayed clearing. Most of the delayed clearing faults assumed protection system failure, so the fault took longer to clear but no additional branches were tripped. Only a few faults were analyzed with delayed clearing due to breaker failure. Future studies should examine more single-line-to-ground faults with breaker failure. Clark Co 345 would be especially interesting. Breaker configurations will need to be known or assumed.

The interconnection request states that 3500 MW may be injected at the AEP Sullivan converter, with the AMMO Palmyra Tap converter running at 0 MW. This operating state will need to be examined in a future study. It will certainly add further stress to the AEP transmission system near Sullivan.

Solutions Proposed

For the stability problems seen at the SPP and AEP ends of the project, the primary solutions involved tripping parts of the GBX project – wind generation and/or HVDC flow – following certain faults. These types of solutions are generally considered Special Protection Systems (SPS) and are not favored by some utilities. SPS's add more complexity and modes of failure to an already complex electric grid. Passive solutions such as new transmission lines or reduced project size may also need to be considered. The PTI report included a sensitivity test of reducing the project size by half. This option showed stable results without an SPS.

Wind Farm Design

The PTI report shows that tripping some of the wind generation can eliminate instability following some NERC Category C faults. While this amount was shown to work for the studied base cases, the project should be designed to be able to adjust this tripping amount easily as system conditions change. An alternative may be to state the maximum MW that can remain on-line following specific contingencies. Because wind generation is variable, this method may be easier to implement and could result in less tripping of wind generation.

Such a large amount wind generation (3700 MW) added to the power system needs to support grid frequency the same as any other large plant such as nuclear or coal-fired. Two important controls that are now available for wind turbines allow both inertia- and governor-like response from wind turbines. For the inertia response, the wind turbine controls take energy out of the spinning blades, slowing their speed, and inject that energy into the electric grid. This is similar to the inertia response from synchronous generators, except that the wind turbine response is actively implemented by controls, as opposed to the natural response of synchronous generators.

For a governor-like control, the wind farm may not be able to ramp up power in response to low frequency (except for the short-term inertia response just discussed) because a wind farm typically runs at its maximum available output all the time. However, with the right controls, wind turbines can respond to high frequency by reducing power output. For a wind farm development as large as this project, it is especially important that the latest advanced controls be included to help support the electric power grid.

5. Conclusions

The results of the PTI report on the Grain Belt Express project have been confirmed by this study. The following mitigation options were confirmed to eliminate the unstable responses:

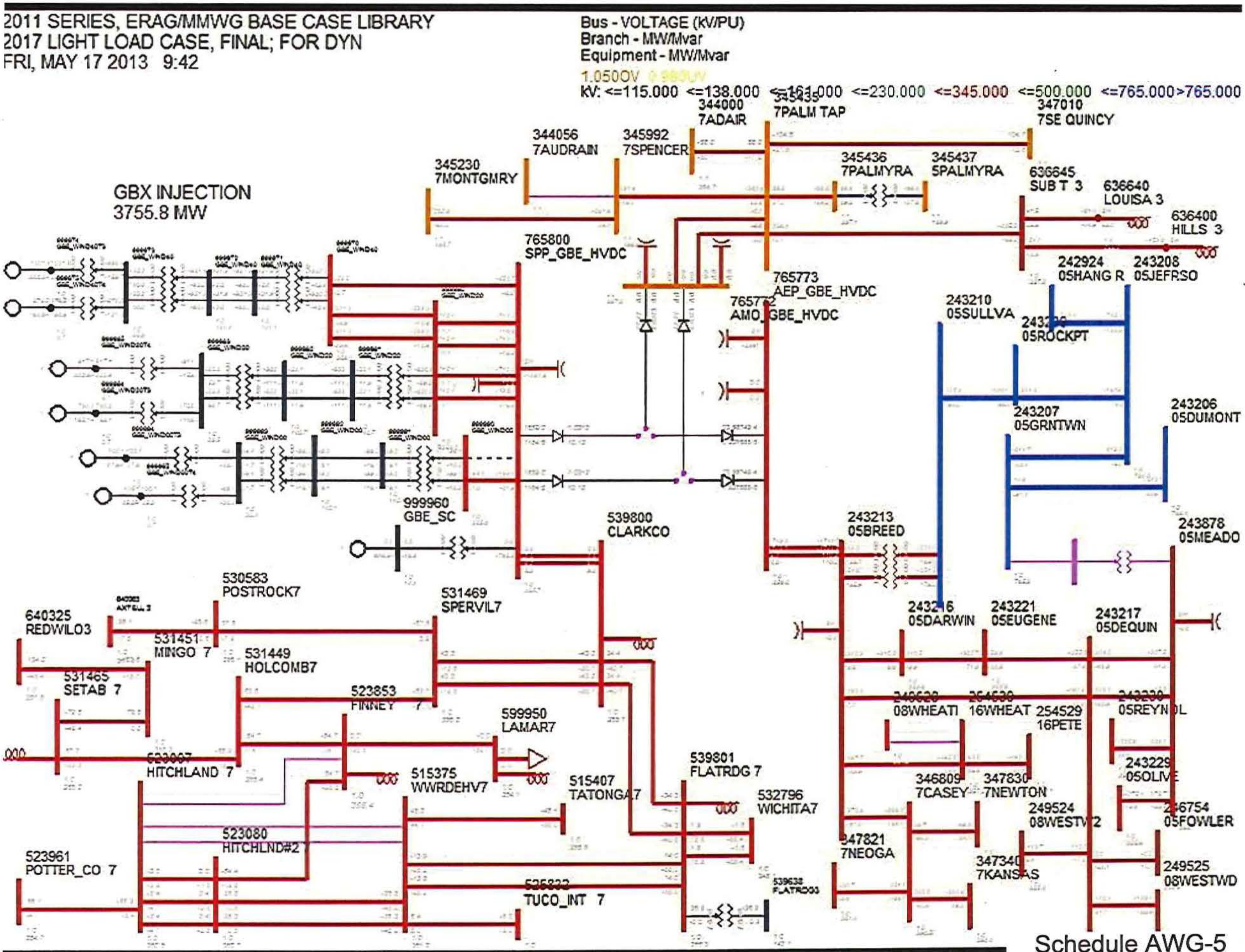
- A 900 Mvar Synchronous Condenser was assumed in all cases
- An SPS to reduce GBX wind generation following parallel circuit outages at Clark Co. Up to 1650 MW of wind generation tripping may be needed for certain double line outages.
- An SPS to reduce HVDC power following outage of the Rockport-Jefferson 765 kV line.

It will be critical for the GBX project to maintain a balance in both its MW flow and its Mvar flow. The project is designed to have a normal power exchange with SPP of 0 MW and 0 Mvar. This target also needs to be maintained during dynamic conditions as best as possible.

Additional considerations for futures studies of the GBX project include:

- Consideration of more breaker failure faults.
- Inclusion of other planned wind generation in the SPP footprint.
- Modeling the maximum 3500 MW HVDC injection at the AEP Sullivan end.
- If the SPS solutions are not acceptable, other solutions such as new transmission lines or reduced GBX project size will have to be found.

The results of this study depend on the assumed models for the HVDC equipment, wind generators, wind collector system, and the power systems in the area of the project. Some of these assumptions will surely change or come into better focus as the project moves forward. The stability analysis will need to be repeated when the assumptions are better defined.


2011 SERIES, ERAG/MMWG BASE CASE LIBRARY
2017 LIGHT LOAD CASE, FINAL; FOR DYN
FRI, MAY 17 2013 9:42
Bus - VOLTAGE (kV/PU)
Branch - MW/Mvar
Equipment - MW/Mvar
1.050OV
kV: <=115.000 <=138.000 <=161.000 <=230.000 <=345.000 <=500.000 <=765.000>765.000
GBX INJECTION
3755.8 MW
344000
7ADAIR
345435
7PALM TAP
347010
7SE QUINCY
344056
7AUDRAIN
345992
7SPENCER
345230
7MONTGMRY
345436
7PALMYRA
345437
5PALMYRA
636645
SUB T 3
636640
LOUISA 3
636400
HILLS 3
765800
SPP_GBE_HVDC
765773
AEP_GBE_HVDC
765772
AMO_GBE_HVDC
242924
05SHANG R
243208
05JEFRSO
243210
05SULLVA
05ROCKPT
243207
05GRNTWN
243206
05DUMONT
999960
GBE_SC
539800
CLARKCO
243213
05BREED
243878
05MEADO
530583
POSTROCK7
531469
SPERVIL7
640325
REDWIL03
531451
MINGO 7
531449
HOLCOMB7
531465
SETAB 7
523853
FINNEY 7
599950
LAMAR7
HITCHLAND 7
515375
WWRDEHV7
515407
TATONGA7
539801
FLATRDG 7
532796
WICHITA7
523080
HITCHLND#2 7
523961
POTTER_CO 7
TUCO_INT 7
243216
05DARWIN
243221
05EUGENE
243217
05DEQUIN
08WHEATI
16WHEAT
254529
16PETE
05REYNOL
243229
05OLIVE
346809
7CASEY
347830
7NEWTON
249524
08WESTV2
246754
05FOWLER
347821
7NEOGA
347340
7KANSAS
249525
08WESTWD

MISO Project Number	J255	County	Marion
Point of Interconnection	Palmyra Tap 345kV substation	State	MO
Summer Net Output (MW)	500	Control Area	Ameren

Summer Off Peak

Monitored Element	Contingency	DF (%)	Rating (MVA)	Overload (%)	FCITC (MW)	Voltage (kV)
N/A	N/A	N/A	N/A	N/A	N/A	N/A

Summer Peak

Monitored Element	Contingency	DF (%)	Rating (MVA)	Overload (%)	FCITC (MW)	Voltage (kV)
N/A	N/A	N/A	N/A	N/A	N/A	N/A

DPP Entry Milestone
$1,555,848

See Attachment A for M2 Milestone Payment Calculation

N/A indicates no constriants have been found based on the scope of the feasilbity screening.

MISO Project Number	J255	County	Marion
Point of Interconnection	Palmyra Tap- Montgomery 345 kV Line	State	MO
Summer Net Output (MW)	500	Control Area	Ameren

Summer Off Peak

Monitored Element	Contingency	DF (%)	Rating (MVA)	Overload (%)	FCITC (MW)	Voltage (kV)
N/A	N/A	N/A	N/A	N/A	N/A	N/A

Summer Peak

Monitored Element	Contingency	DF (%)	Rating (MVA)	Overload (%)	FCITC (MW)	Voltage (kV)
N/A	N/A	N/A	N/A	N/A	N/A	N/A

DPP Entry Milestone
$1,555,848

See Attachment A for M2 Milestone Payment Calculation

N/A indicates no constriants have been found based on the scope of the feasilbity screening.

Attachment A

Voltage (kV)	Cost ($)
345	350,000
230	200,000
161	130,000
138	130,000
115	130,000
69	125,000

M2 Milestone Payment = 10% x (Total for Number of Feasibility Constraints per Voltage Level x Constant Cost (see chart above) per Voltage Level + Project Size (MW) x Current Schedule 7 MISO Drive-Through and Out Yearly Rate)

Maximum Cost = $10,000 per Gross MW, Minimum Cost = $2,000 per Gross MW

Schedule 7 MISO Drive-Through and Out rate = $31116.9670

N/A indicates no constriants have been found based on the scope of the feasilbity screening.

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ORNL/Sub/95-SR893/2

HVDC Power Transmission Environmental Issues Review

William H. Bailey
Deborah E. Weil
BRAI

James R. Stewart
PTI

MANAGED AND OPERATED BY
LOCKHEED MARTIN ENERGY RESEARCH CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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HVDC POWER TRANSMISSION ENVIRONMENTAL ISSUES REVIEW

ORNL/Sub/95-SR893/2

William H. Bailey, Deborah E. Weil (BRAI)
James R. Stewart (PTI)

Published April 1997

Report Prepared by

New England Power Service Company
25 Research Drive
Westborough, MA 01582
and
Power Technologies, Inc.
P.O. Box 1058
Schenectady, NY 12301
and
Bailey Research Associates, Inc.
292 Madison Avenue
New York, NY 10017

for

OAK RIDGE NATIONAL LABORATORY
P.O. Box 2008
Oak Ridge, Tennessee 37831

managed by
LOCKHEED MARTIN ENERGY SYSTEMS

for the
U.S. DEPARTMENT OF ENERGY
under Contract DE-AC05-96OR22464

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ACKNOWLEDGEMENTS

This work was funded and managed by the U.S. Department of Energy, Offiice of Utility Technologies as part of their Transmission and Distribution research and development program. The following three reports document the completed work:

ORNL/Sub/95-SR893/1 "HVDC Power Transmission -Technology Assessment"
ORNL/Sub/95-SR893/2 "HVDC Power Transmission - Environmental Issues Review"
ORNL/Sub/95-SR893/3 "HVDC Power Transmission - Eletrode Siting and Design"

The authors extend their appreciation to John Stovall, Project Manager for ORNL and his steering committee; Dr. Willis Long of the University of Wisconsin, Phil Overholt of DOE, Mark Reynolds of Bonneville Power Administration, and Duane Torgerson of Western Area Power Administration for their invaluable guidance during this project. Our appreciation also to Messrs. Jeff Donahue, Dan Lorden and Doug Fisher, of New England Power Service Company for their thorough reviews and advice regarding the results of this investigation.

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

---

[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)

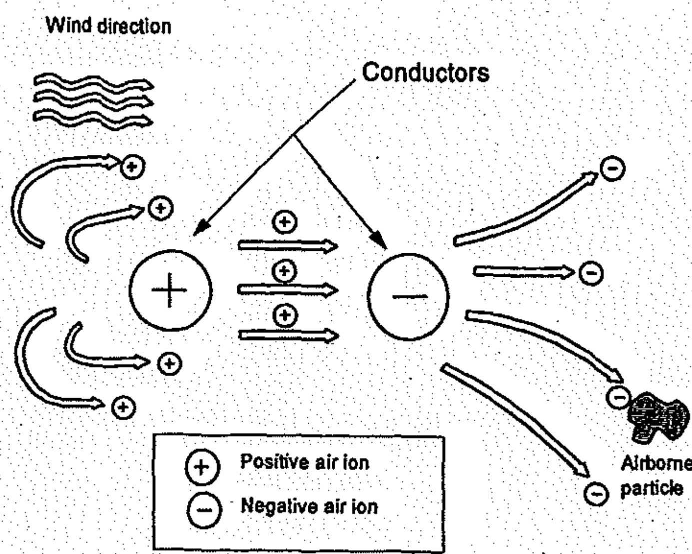

Figure 2.1: Ions drift with the wind, some fall to the ground, others move to the conductor with opposite polarity and are absorbed.

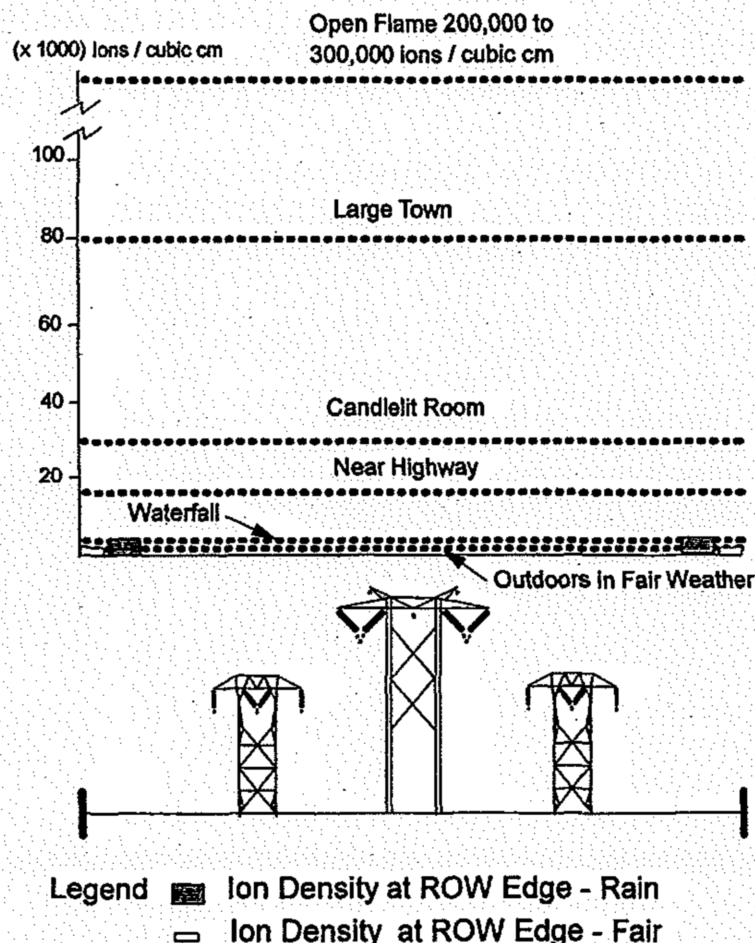

Figure 2.2 Typical ion densities on section of New England Electric's +/- 450 kV dc line between Monroe, NH and Londonderry, NH

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.

<u>Ion Current</u>

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).

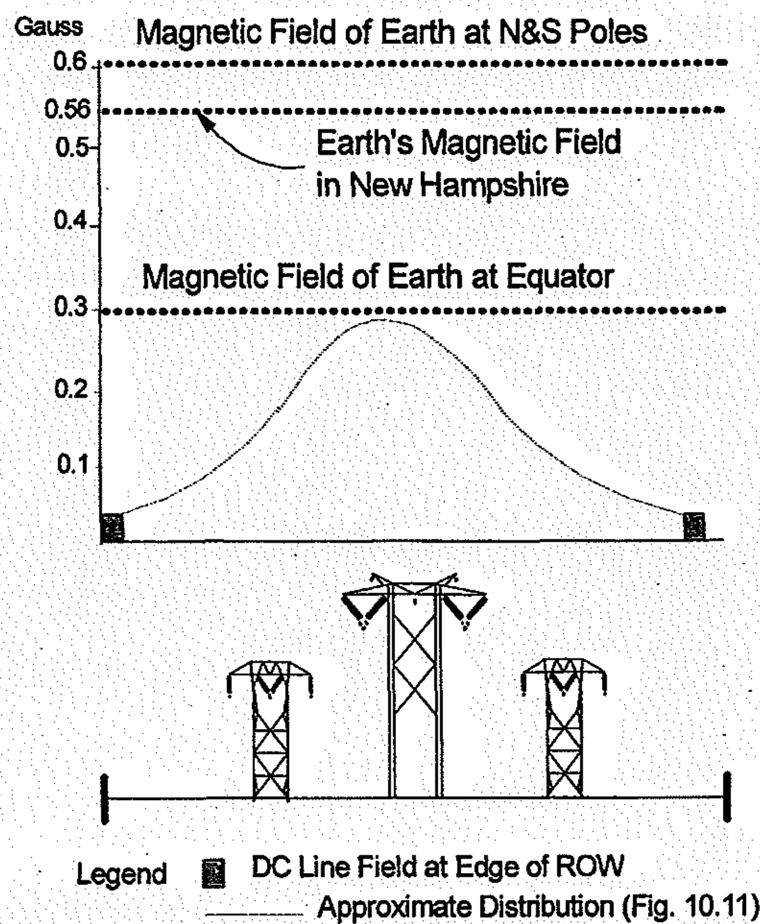

Figure 2.3 Typical magnetic field on section of New England Electric's +/- 450 kV dc line between Monroe, NH and Londonderry, NH

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.

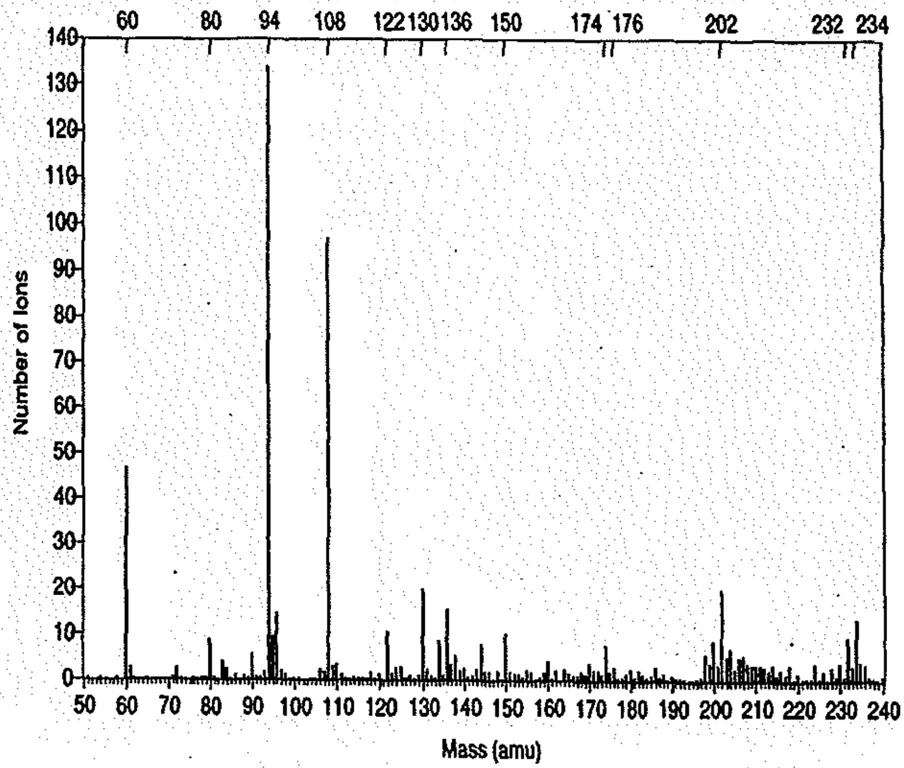

Figure 2.4: Averages of several measurements of the positive air ion mass spectrum observed under the positive conductor of the +/- 500 kV Pacific Intertie. (from Eisel, 1989)

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.

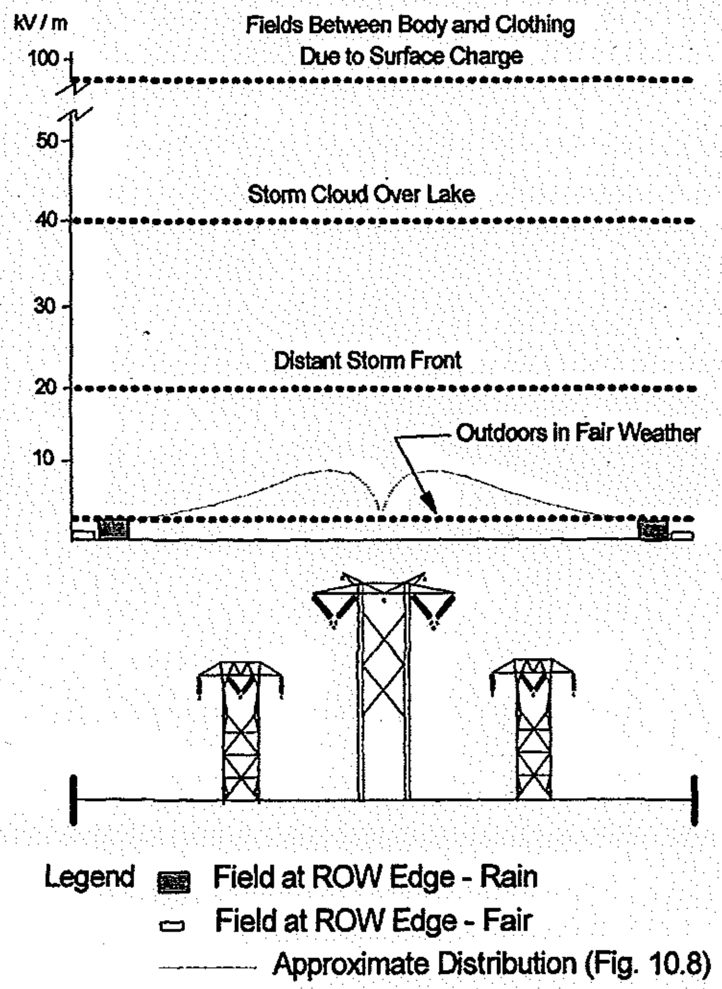

Figure 4.1 Typical electric fields on New England Electric's +/- 450 kV dc line between Monroe, NH and Londonderry, NH. Absolute magnitudes shown -- actual values are negative on one side.

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

[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.

Ion Cyclotron Resonance (ICR)

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).

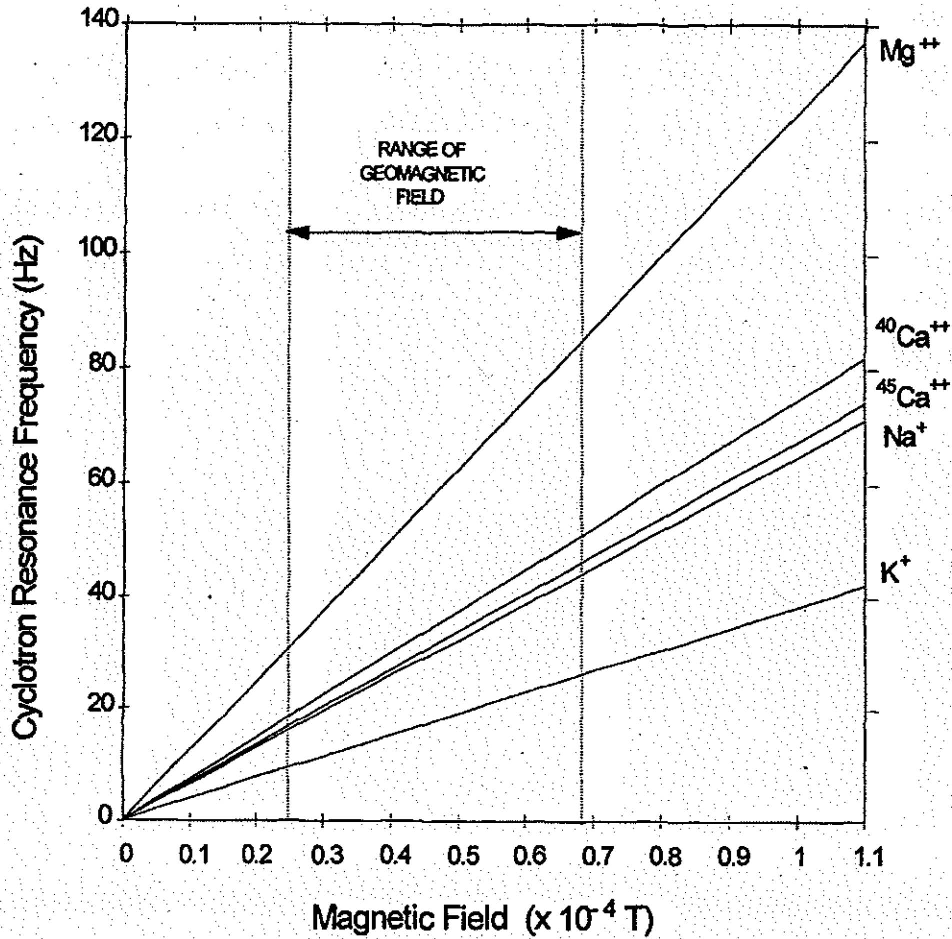

Figure 5.1 Cyclotron resonance (CR) frequency as function of magnetic field for various ions. Range of Earth's magnetic field (total intensity) over the earth's surface is superposed. (Liboff, et al, 1987)

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.

New England - Hydro Quebec Phase I

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.

[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.

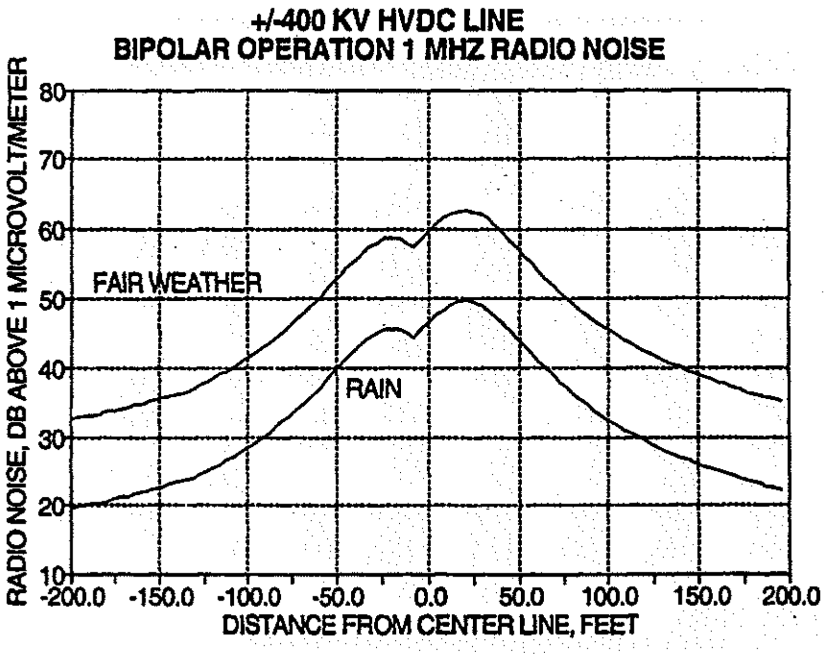

Figure 10.1 RN DC Line Bipolar Operation in Fair Weather

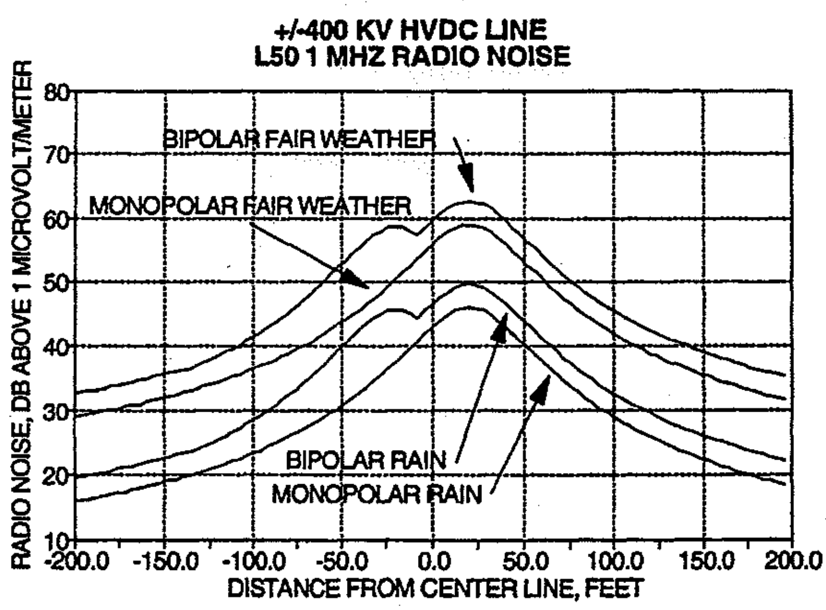

Figure 10.2 RN DC Line Monopolar and Bipolar Operation

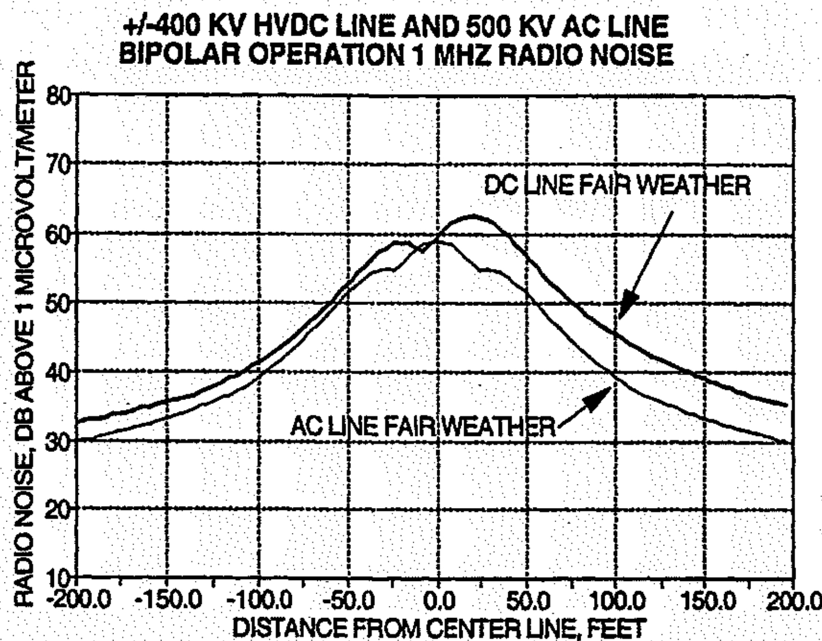

Figure 10.3 RN Comparison of DC and AC Lines in Fair Weather

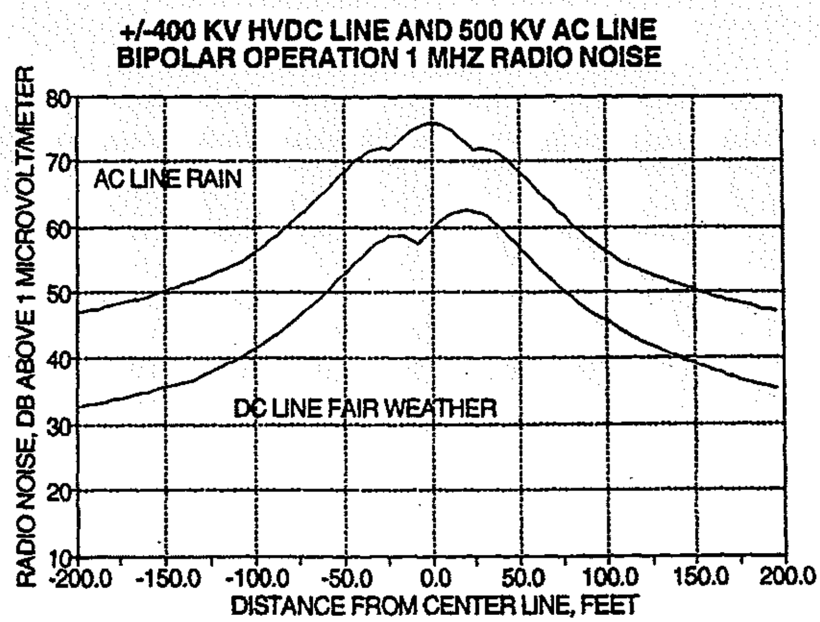

Figure 10.4 RN Comparison of DC Line in Fair Weather and AC Line in Rain

10.2.2 Audible Noise

Audible noise first appeared as a problem when 765 kV ac transmission lines were first introduced. Audible noise, like radio noise, is produced by corona on transmission line conductors. For ac lines, it takes on two forms: a sizzling or crackling sound called random noise and a single pitch tone called hum. Only the random noise component is present for dc lines. Transmission line random audible noise is rich in high frequency components, which gives it a distinctive sound. Both dc and ac lines have similar corona noise frequency spectra.

Random noise results from a multitude of small snapping sounds at corona points on the conductor. Sound propagates through air at approximately 1100 feet per second. The path length, and hence the phase shift, is different from each corona point to the listener. Each sound arrives with a different phase delay and results in the distinctive random noise sound rich in high frequency components.

Audible noise from insulator corona is rarely evaluated. In densely populated countries attention has been given to aeolian noise resulting from wind passing over the conductors, but this is an entirely different subject from electrically-caused corona noise and is entirely independent of whether the line operates dc or ac.

The human ear does not have a linear frequency response. As a result, it is necessary to adjust measured noise levels, given in decibels (dB), to obtain correlation with human ear sensitivity. The correlation is provided by frequency response "weighting" curves. The "A" weighting curve is used for most community noise evaluation studies. Noise calculated or measured with a particular weighting curve is identified with the letter of the curve in parentheses, for example 50 dB(A) for A weighting.

The noise profiles predicted by computer programs assume no obstructions between the line and listener. This is equivalent to saying that the operator has a clear view of the line from horizon to horizon. In practice, however, the farther one moves from the line, the more sound-absorbing trees and vegetation come between the listener and line. The effect of this sound absorption is that measured sound profiles tend to decrease with distance faster than do predicted profiles.

Audible noise from ac transmission lines is generally of concern only in wet conditions. Fair weather audible noise can be sometimes heard, but rarely is it able to be measured because of the presence of background noise. On the other hand, the highest noise levels occur during rain, which can itself mask the noise. Audible noise can be characterized by exceedence levels, typically L_5 and L_{50} foul weather, referred to as "heavy rain" and "wet conductor" conditions, respectively. Other references call these "maximum" and "average" foul weather conditions. The L_{50}, wet conductor, or average foul weather value is the number most commonly used for audible noise evaluation of ac transmission lines. In contrast, audible noise from dc transmission lines is generally greater during fair weather than for rain.

Many jurisdictions have noise abatement ordinances which specify noise at the property line. These ordinances take a number of forms. Some are maximum A-weighted levels. Some have different levels for day and night. Some are equivalent values averaged over a period of time L_{eq} to allow for variations of noise with weather. Others are day-night limits L_{dn} where nighttime noise is more heavily weighted than daytime noise to represent the greater annoyance potential of noise at night. When equivalent averaged values are used for evaluation of audible noise, it is necessary to take into account the relative number of hours for foul weather audible noise (ac lines) versus the number of hours for fair weather audible noise (dc lines).

Figures 10.5-10.7 present the following calculated audible noise lateral profiles for the example dc and ac transmission lines:

10.5 DC line bipolar operation in fair weather and rain
10.6 DC line monopolar and bipolar operation
10.7 Comparison of dc line in fair weather and ac line in rain

Observations from these figures:

- As with radio noise, fair weather audible noise from a dc line exceeds the audible noise during rain.

- Likewise, noise during bipolar operation is greater than noise during monopolar operation.

- For the example lines, audible noise produced by the dc line during fair weather is approximately 15 dB below that produced by the ac line during rain. Thus, the highest sound levels from the dc line should be less of an effect than those from an ac line. For especially quiet locations the impact of the relative number of hours of fair weather versus rain should be factored into an overall assessment of the relative noise. There is also some indication that audible noise from a dc line may be more irritating to people than ac line noise of the same magnitude. This may also be a factor in especially quiet locations.

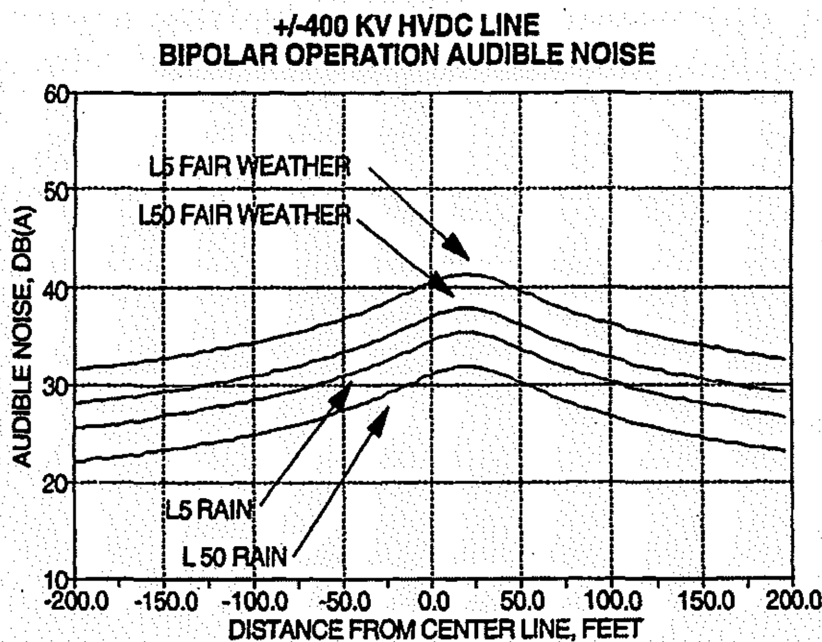

Figure 10.5 AN DC Line Bipolar Operation in Fair Weather and Rain

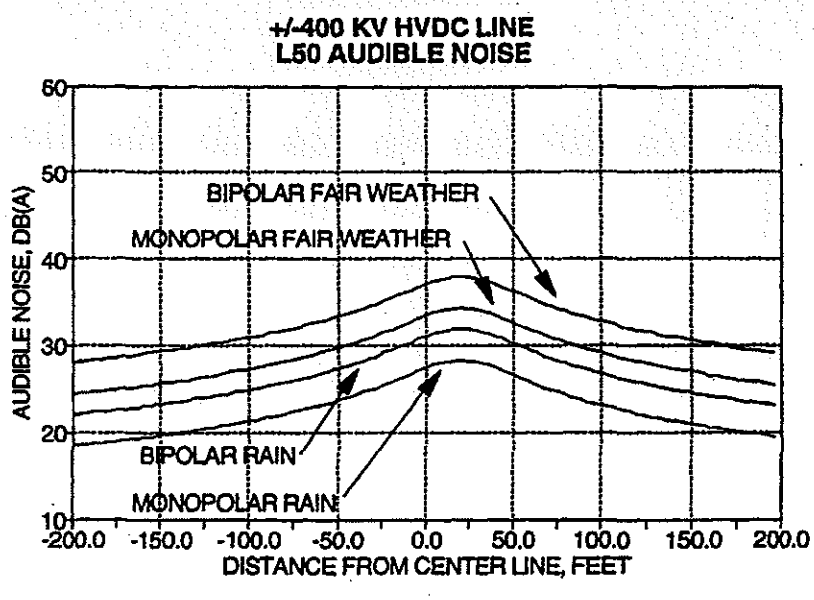

Figure 10.6 AN DC Line Monopolar and Bipolar Operation

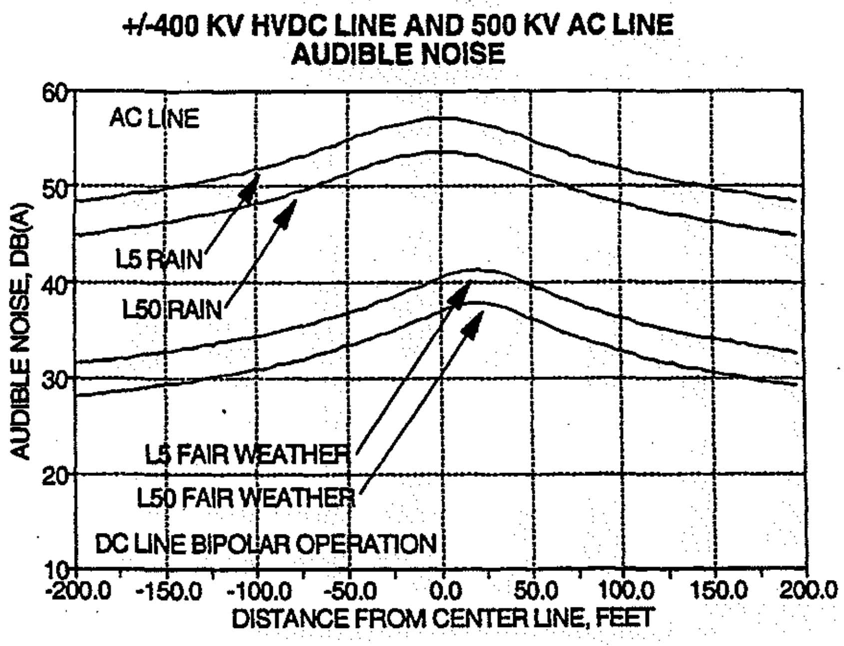

Figure 10.7 RN Comparison of DC Line In Fair Weather and AC Line in Rain

10.2.3 Air Ions

Air ions are natural components of the atmosphere. Ions are molecules with extra electrons (negative ion) or missing electrons (positive ion). They may be produced by such activities as storms, sunlight, blowing dust, and corona. High voltage dc lines typically operate in constant corona and produce air ions by the breakdown of the air molecules adjacent to the conductor (corona). The flow of air ion current equals the corona loss current.

Because of the non-alternating nature of direct current transmission, the air ions migrate away from a dc line instead of being trapped near the line conductors as with an ac line. Because both conductors of a dc line have an electric field, both can produce corona and therefore air ions. Most air ions are attracted to the conductor opposite to the one that generated them. Neutralization occurs when air ions combine with those of opposite polarity. Most air ions from HVDC lines are neutralized. Approximately 10% of the ions escape and migrate away from the transmission line, filling the space between line conductors and ground. A unipolar space charge region exists under each of the conductors, and a bipolar space charge region between the conductors. Migration of ions is a function of ion mobility as well as atmospheric conditions. The migrating air ions are carried away by wind, much like dust particles or pollen. Therefore, few air ions produced by the dc line are present on the upwind side of the line. Downwind air ion concentrations have been measured up to ½ mile from a dc line, although only for a small fraction of time.

Early research on laboratory lines indicated that positive pole ion activity is greater than negative pole ion activity, much as positive pole radio and audible noise is greater than negative pole radio and audible noise. Measurements on operating lines have found negative pole ion activity as anticipated, but positive pole ion activity suppressed. The difference in ion production between laboratory lines and operating lines is caused by the effect of elevated air temperature near the conductors resulting from resistive heating of the conductors from the load current. Passage of load current raises the conductor temperature, and therefore decreases the relative air density of the air surrounding the conductor. Ion production is a function of relative air density, so by this means line current has an influence on ion production.

The electric field from a dc line is a random variable. In foul weather a charge sheath forms around the conductor, which decreases the electric field near the conductor (reducing audible and radio noise), but increases the ground level field. The electrical environment surrounding a dc transmission line is therefore composed of three parts:

- The electric field which exists in the absence of ions in kV/m, frequently called the electrostatic field.
- Ion current density in Amperes per square meter (A/m^2).
- Space charge density (small air ions and charged aerosols) in $ions/cm^3$ or charge density in $Coulombs/m^3$.

The total electric field measured near a dc line is the sum of that produced by charge on the line conductors in the absence of ions, plus the effect of the space charge. Migration of the space charge because of the force caused by the electric field causes an ion current density in the space surrounding the line.

Even under stable weather conditions, the total ground level electric field and ion current density vary over a wide range, making prediction difficult. During fair weather, the effect of the space charge is rarely to decrease the electric field below that expected from line conductor charge alone, and may increase the electric field to a maximum strength 2 to 4 times that due to the line conductors alone. Ion activity generally increases during rain for dc lines, although the maximum electric field and ion current density in rain may not be greater than those in fair weather. The maximum value of ground level electric field including the effect of the space charge is the value of the uniform field given by line voltage divided by conductor height.

The magnitude of ion current is on the order of hundreds of nanoamperes per square meter. The current intercepted by a person standing under a dc line is on the order of a few microamperes, several orders of magnitude below that needed to perceive a shock. The ion current density deposits charge on nearby objects, causing a surface voltage build-up if the object is well insulated from ground. The amount of charge accumulated depends on the size of the object, its location with respect to the line, and its resistance to ground. As a practical matter, people and other objects normally have a sufficiently low resistance to ground to limit the charge accumulation to very low levels. If a sufficiently high resistance exists, a large object may store enough energy to deliver a shock similar to that experienced by walking on a carpet in winter and touching a door knob. This charge is on the order of 5-10 millijoules. There is insufficient current density to sustain a steady current shock. This is in contrast to ac transmission lines, where electric field induction can result in both transient spark and steady state current effects.

DC electric fields induce a static charge on the surface of conducting objects near the line. This may result in discharges similar to insulated objects charged by ion deposition. Perceptible spark discharges may thus occur from both insulated and conducting objects in the field of a dc line.

Hair stimulation and other sensations experienced by the skin may result in human perception of the field. The same phenomenon holds for ac transmission lines. The threshold of perception for the electric field from a dc line is greater than the threshold of perception from an ac line. Thus, a dc electric field is generally less bothersome to work or be in than an ac electric field of the same level.

While not an environmental effect to the public, electric field and ion current induction are factors for safe live-line maintenance of an energized dc line. Tests have shown that a helicopter-airborne platform can be safely used to perform live-line work.

10.2.4 Corona loss

Corona loss is the electrical energy loss resulting from corona activity on the conductors. This loss is proportional to corona current, which can be measured when corona is the only electrical load on the conductors. Corona loss varies with weather conditions. It is a function of wind speed, rain, snow, and fog. There is also a slight dependence on relative humidity. Corona loss typically increases by a factor of 2 to 5 in precipitation, with a maximum factor of 10. Corona loss may be a factor in the economic choice of conductor bundles, but is not an environmental concern.

10.2.5 Ozone

Conductor corona activity produces small amounts of ozone. Ozone production rates depend on the corona loss, and thus correlates to the same weather conditions as corona loss. Wind tunnel tests indicate ozone production rates about three times larger for the negative pole than for the positive pole for the same corona current. Tests indicate these wind tunnel tests are indicative of ozone production on operating lines.

During fair weather, ozone production from an HVDC line is not detectable in the variability in natural ozone. Under certain precipitation conditions, it is rarely possible to detect corona-produced ozone downwind from a +/- 500 kV HVDC line at the height of the conductors on the order of less than 2 parts per billion. The difficulty of making this small measurement indicates that ozone is not a factor in environmental assessment of HVDC lines.

10.3 ELECTRIC FIELD EFFECTS

The electric field of an ac transmission line induces voltages on nearby objects by the capacitive voltage divider between line, object, and ground. These objects are typically vehicles, people, animals, sheds, and similar sized bodies. Evaluation of electric field effects of ac lines involves human perception, annoyance, and safety with respect to voltages and currents induced on these nearby objects. The electric field of a dc transmission line is static and therefore unable to induce voltages on nearby bodies by capacitive coupling. Deposition of charge and induction of voltage and current by ion phenomena from dc lines have been addressed in the section on air ions.

The electric field of a dc line in the absence of space charge (the electrostatic field) is a useful benchmark for comparing dc and ac lines. Figures 8-9 present the following calculated electric field lateral profiles for the example dc and ac transmission lines:

10.8 DC line monopolar and bipolar operation
10.9 Comparison of dc line and ac line

The maximum electric field under the line during monopolar operation is greater than that during bipolar operation. The maximum electric field under the dc line for bipolar operation is greater than that for the ac line. DC lines typically operate at higher ground level electric fields than ac lines, because dc lines are not subject to the same capacitive induction that ac lines experience.

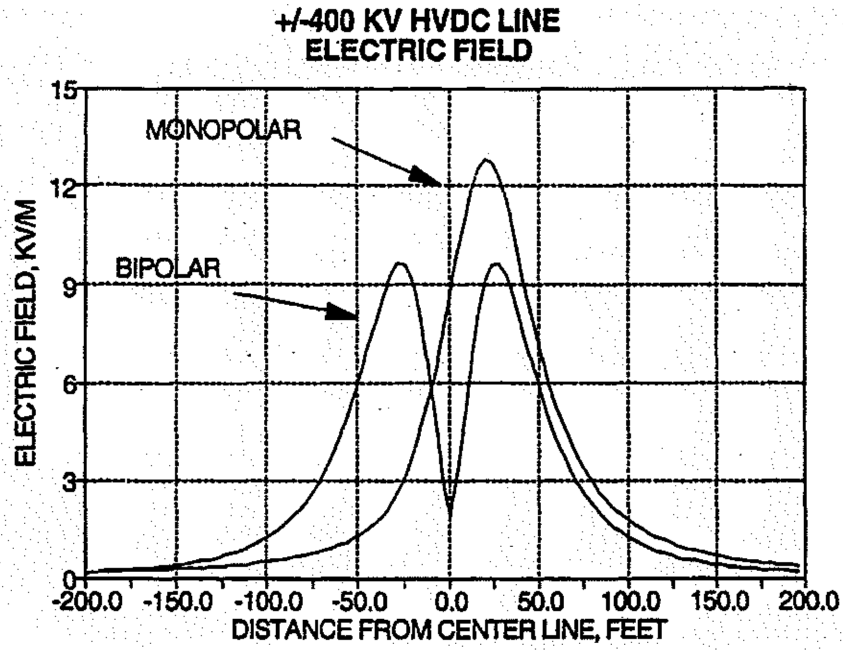

Figure 10.8 EF DC Line Monopolar and Bipolar Operation

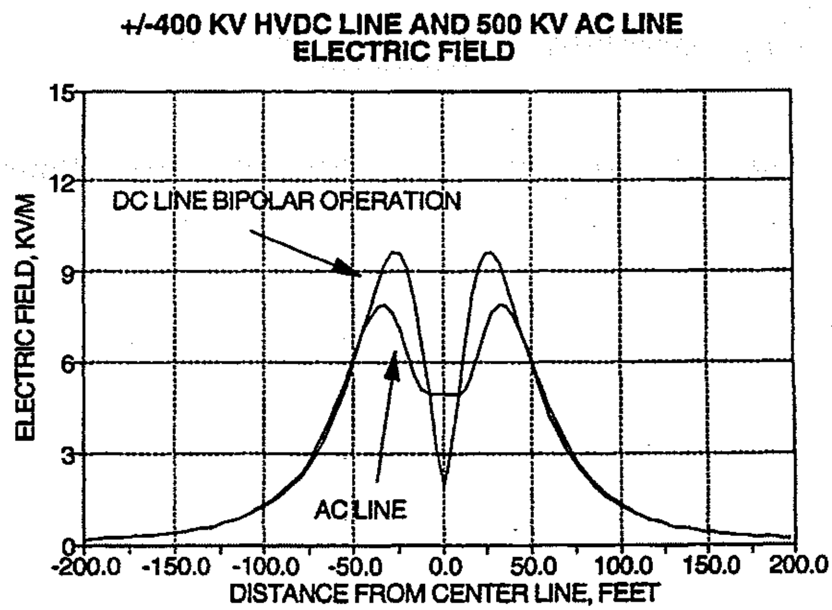

Figure 10.9 EF Comparison of DC Line With AC Line

10.4 MAGNETIC FIELD EFFECTS

The magnetic field of an ac transmission line induces voltages on nearby objects by inductive coupling between the line and nearby parallel objects such as pipelines, long fences, telephone lines, and railroads. As with electric fields, evaluation of magnetic field effects of ac lines involves human perception, annoyance, and safety with respect to voltages and currents induced on these nearby objects. In addition to human safety, inductive effects of ac lines include possible interference to railroad signals, noise in telephone circuits, and possible impairment of pipeline cathodic protection systems. The magnetic field of a dc transmission line is static, and therefore unable to induce voltages on nearby bodies by inductive coupling.

Figures 10.10-10.11 present the following calculated magnetic field lateral profiles for the example dc and ac transmission lines:

10.10 DC line monopolar and bipolar operation for three line loading levels
10.11 Comparison of dc and ac lines at 1000 MW each

Monopolar operation of the dc line results in larger magnetic field than bipolar operation at the same pole current. For the same circuit loading, the magnetic field profiles of the example dc and ac lines are similar.

An effect of magnetic field of a dc line which is not present for an ac line is deflection of a compass needle near the line. This is potentially significant for a dc line crossing or near a navigational channel. Figures 10.12-10.14 present calculated compass needle deflection at 3 feet above ground level for the example dc transmission line under the following conditions:

10.12 Bipolar operation at 1000 MW loading
10.13 Monopolar and bipolar operation for three line loading levels
10.14 Monopolar and bipolar operation at greater distances from the line

Within 50 feet of the center of the line the compass needle deflects as much as 33 degrees from magnetic north. Maximum deflection is greater for monopolar operation than it is for bipolar operation. For monopolar operation the deflection is only in one direction, rather than swinging about zero as is the case for bipolar operation. Beyond about 300 feet from the line the deflection is less than 1 degree, even for maximum current and monopolar operation. Concern is sometimes expressed about a possible effect of dc lines on migratory birds, because they use the earth's magnetic field for navigation during migration. The effect of the dc line would be at most a few degrees course error for a few feet of flight, less than would be expected from wind currents.

A magnetic field influence common to both ac and dc lines is their effect on the display of video display terminals. AC power frequency magnetic field beyond 10 mG can cause jitter of the display, depending on the particular terminal. DC magnetic field can cause deflection of the image and color distortion. Jitter from ac magnetic fields is visible at lower field strengths than deflection or color distortion from dc magnetic fields. The comparable field profiles between dc and ac lines indicated in Figure 10.12 indicates that computer monitor interference is less of a concern for dc lines than for ac lines of comparable loading.

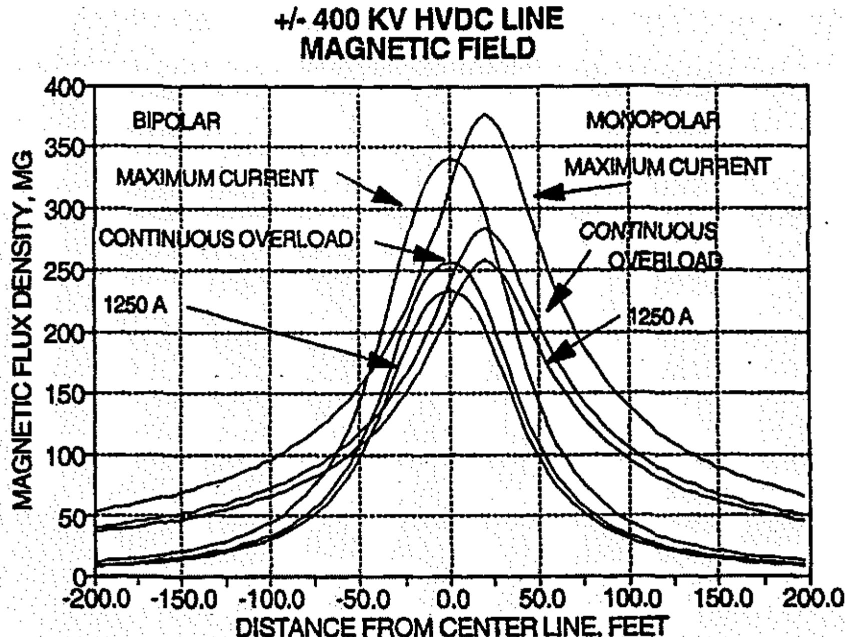

Figure 10.10 MF DC Line Monopolar and Bipolar Operation

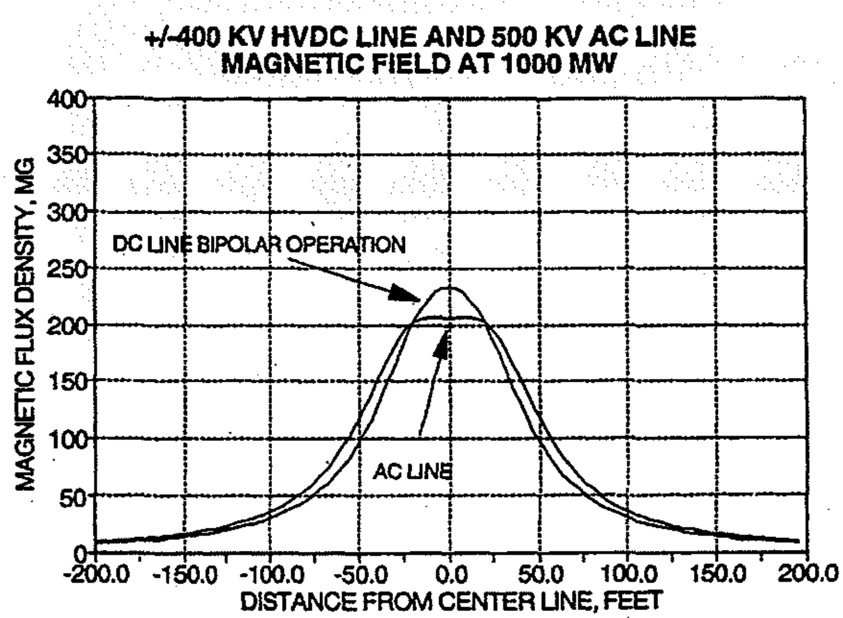

Figure 10.11 MF Comparison of DC and AC Lines at the Same Loading

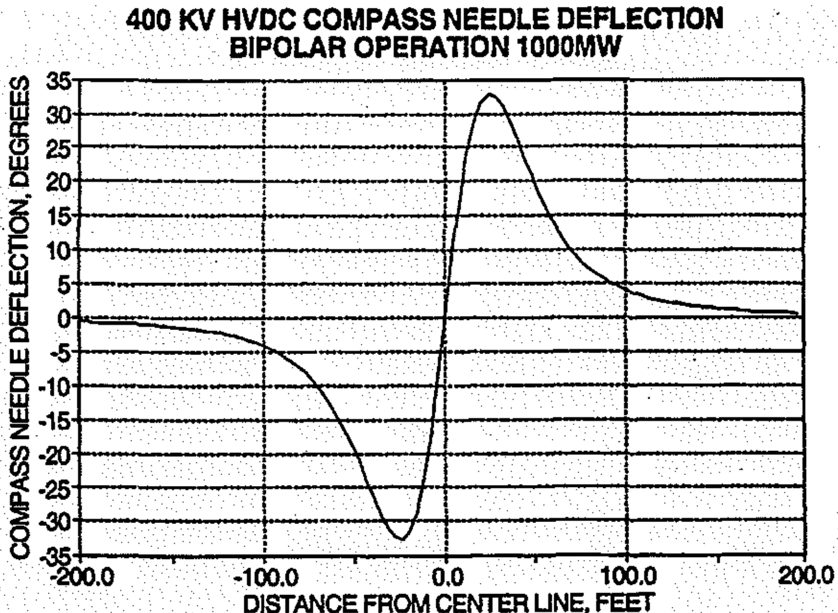

Figure 10.12 Bipolar Operation Compass Needle Deflection

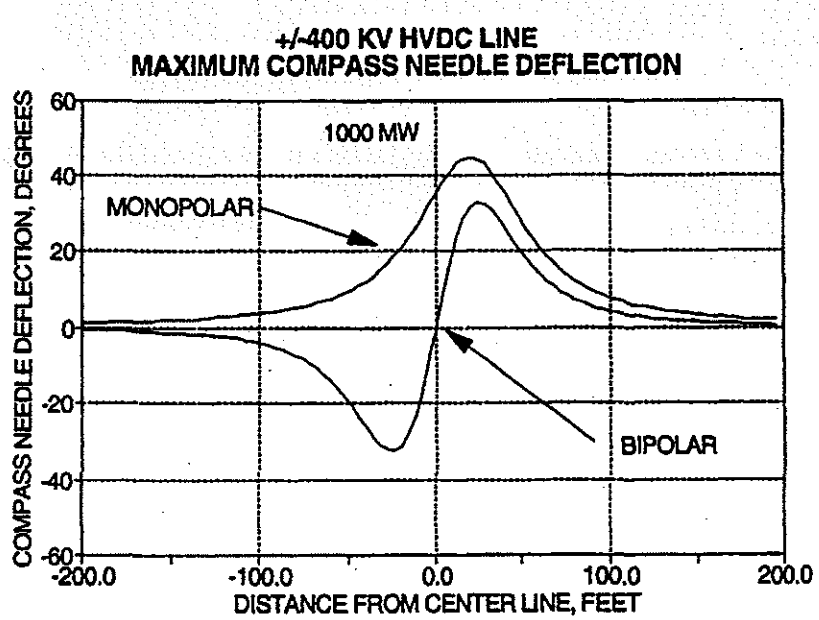

Figure 10.13 Compass Needle Deflection Monopolar and Bipolar Operation

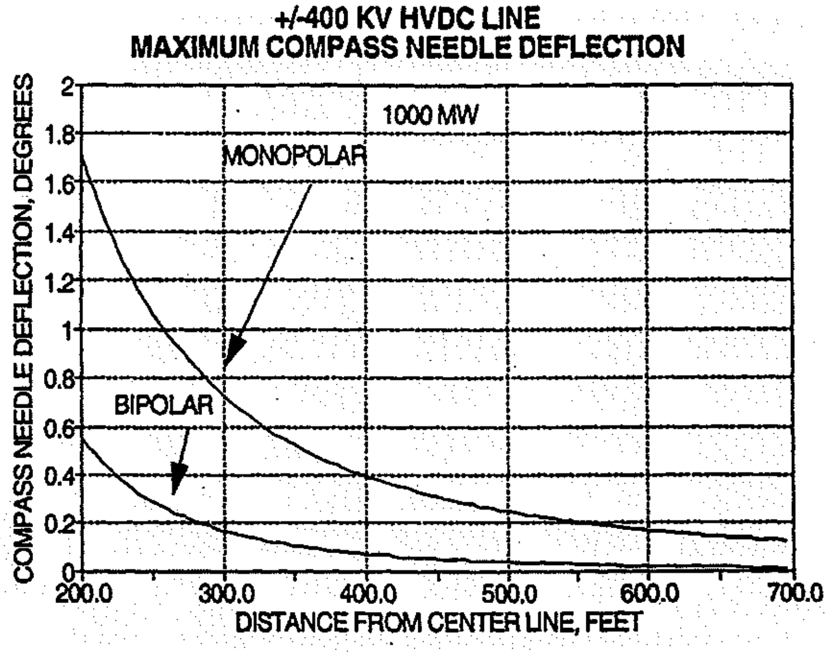

Figure 10.14 Compass Needle Deflection Far From DC Line

10.5 COORDINATION WITH PARALLEL FACILITIES

Possible interference to power line and open wire carrier installations caused by HVDC converter stations was addressed in the section on radio interference. Inductive coordination of ac power lines and telephone lines is virtually as old as the utility industry. Inductive coupling from power frequency and harmonic currents into parallel telephone lines have been extensively studied. The steady current in a dc transmission line does not induce voltage in parallel facilities, but harmonic frequency currents do exist on both the dc and ac side of converter stations. Induced noise voltage is highest for monopolar earth return, less for monopolar metallic return, and lowest for bipolar operation. Filters designed into the converter stations are very effective in reducing induced noise voltage.

While there is no steady-state induction of voltages or currents to pipes and fences parallel to a dc transmission line, there is the possibility of voltages and currents due to transient line current during fault conditions or line switching. There normally is insufficient energy coupled during a single fault transient to be of concern for safety for facilities adequately grounded for lightning protection.

10.6 HYBRID AC/DC TRANSMISSION LINES

There is increasing probability as use of dc power transmission increases that ac and dc lines will share the same right-of-way, or even be constructed as double circuit lines. The phrase "hybrid" ac/dc transmission lines refers to ac and dc circuits sharing common support structures or right-of-way. In such situations it is necessary to consider field and ion interactions between the two circuits. These interactions have both environmental and system operation consequences. System operation concerns include:

- Relay misoperation due to zero sequence currents induced in the ac lines by transients in the dc lines.
- Consequences of faults involving both the dc and ac circuits.
- Effects on dc converter station operation caused by induction from the ac line.
- Transformer saturation on the ac system resulting from dc currents coupled from the dc line.

The presence of the dc line causes a dc component of electric field at the surface of the conductors of the ac line. Likewise, the presence of the ac line causes an ac component of electric field at the surface of the conductors of the dc line. Because conductor corona radio and audible noise are functions of the maximum electric field at the conductor surface, this additional field component has an effect on radio and audible noise of the hybrid configuration.

Positive corona is the major contributor to radio and audible noise, whether the transmission line is dc or ac. Negative dc fields enhance positive ac transmission line corona activity, increasing radio and audible noise from the ac line. Positive dc fields suppress positive ac transmission line corona activity, decreasing radio and audible noise from the ac line. The relative arrangement of the circuits thus may increase or decrease the overall noise. In foul weather the ac conductors are the predominant source of audible noise, the level being increased if the ac conductors are near the negative dc conductor.

For dc and ac circuits on adjacent towers, the ground level electric field, ion density and ion current density are approximately the same as they would be for both circuits calculated separately. When the dc and ac circuits are constructed on the same structure, there can be an appreciable interaction between them, the details of which depend on the relative layout of the circuits on the structure. If the ac circuit is constructed beneath the dc circuit, there is a shielding of the dc line electric field, ion density, and ion current density at ground level. Increased electric field at the surface of the conductors of the ac line, however, results in increased radio and audible noise from the ac line. In general, the ac conductors behave as active shield wires for the dc circuit by emitting a compensating dc corona which reduces the dc electric field and ion densities. If the dc circuit is constructed beneath the ac circuit, the dc poles act as shield wires for the ac line, reducing the ac electric field at ground level.

One truly interactive effect is human perception of the electric field from a hybrid line. The stimulation of a person by a dc and an ac electric field acting together is considerably greater than for either field acting alone. For example, a typical person in a 15 kV/m ac electric field would experience perceptible, but not annoying sensation. A typical person in a 15 kV/m dc electric would not be able to perceive the existence of the field. However, in a combined 15 kV/m ac and 15 kV/m dc electric field, a typical person would find it intolerable. This is a true interaction, and must be considered when ac and dc lines are installed in close proximity to each other.

The magnetic field environment of hybrid ac/dc transmission lines is the sum of the fields of each line individually, and no special considerations need to be taken for installation of hybrid lines from a magnetic field standpoint.

Corona and field effects of hybrid ac/dc lines are slightly more complicated to analyze than for either type alone, but the mutual interactions from an environmental standpoint are not sufficient to incur a practical hindrance to their use.

10.7 EXAMPLE: CONVERSION OF AC LINE TO DC

Chapter 5 of the Task 1 report discusses conversion of existing ac overhead transmission lines to dc as a means of making optimum use of limited corridors. An example is presented for conversion of an existing double circuit 230 kV ac line to 188 kV dc. In addition to the insulation requirements which must be met for successful dc operation, it is prudent to make an assessment of electrical environmental effects.

Figure 10.15 shows lateral profiles for fair weather radio noise for both ac and dc operation for the same structure and conductors. Fair weather is frequently assumed for a radio noise evaluation because it is generally the most prevalent weather condition. Radio noise is plotted for the following three conditions:

- Double circuit ac line at 230 kV with superbundle phasing (identical phasing for both circuits). Superbundle phasing is the most common arrangement for older circuits. It has lower conductor surface electric field and smaller corona effects, but higher ground level electric and magnetic fields than low reactance phasing.

- Triple circuit dc line operating at 190 kV with the same polarity on all three circuits (positive pole on the left side of the structure).

- Triple circuit dc line operating at 190 kV with the positive pole on the right side of the structure on the center circuit.

The dc configuration with the same polarity on all three circuits has the lower radio noise profile, comparable with that of the existing ac line. Which polarity is chosen would be based on a complete analysis as described in the earlier sections of this chapter.

Figure 10.16 shows lateral profiles for L_{50} fair weather audible noise for dc operation and L_{50} rain audible noise for ac operation for the same structure and conductors. These conditions correspond to those most likely to produce complaints from nearby people. With either relative polarity the dc line audible noise is at least 10 dB below that of the ac line.

Figure 10.17 shows lateral profiles of electric field for the same dc and ac comparison. Electrostatic field magnitude is given for the two dc line polarities, ignoring the effect of air ions on the field profiles. Reversing the polarity of the center circuit reduces the ground level electric field profile. Reversing the polarity of the center circuit will also probably trap a larger percentage of air ions and reduce the ion concentration at ground level.

Figures 10.18 and 10.19 show lateral profiles of magnetic field for the same dc and ac comparison. As with electric field, reversing the polarity of the center circuit reduces the ground level magnetic field profile. Figure 10.18 shows magnetic field profiles for the same total megawatts for dc and ac operation, and Figure 10.19 shows profiles for all conductors at 1000 amperes for all cases. For both electric and magnetic fields the profile for ac operation lies between the profiles for the two relative polarities for dc operation.

A full analysis requires establishment of criteria and evaluation of the predicted values. A preliminary examination of Figures 10.15 through 10.19 indicates that conversion of the example double circuit 230 kV ac line to triple circuit 190 kV dc is feasible from an electrical environmental standpoint.

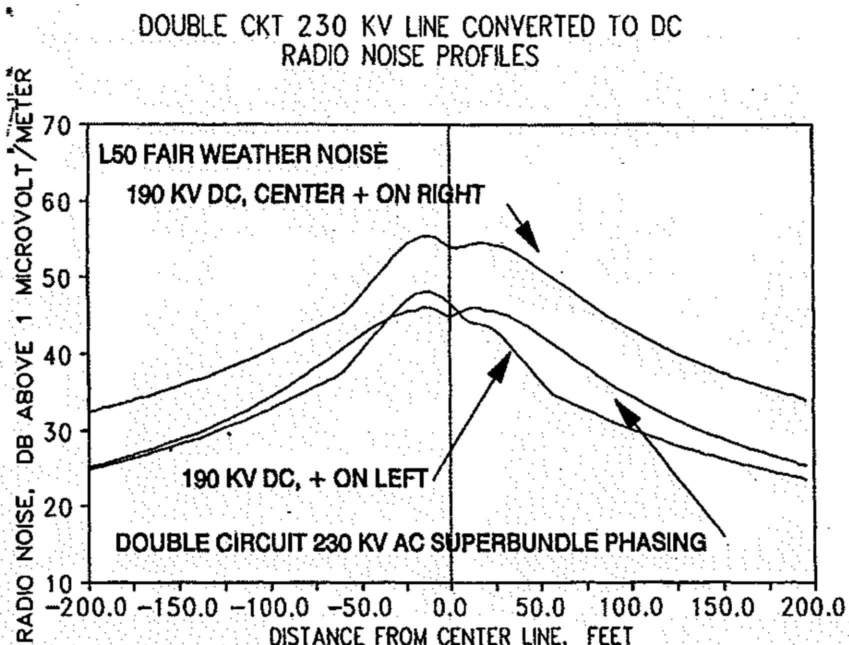

Figure 10.15 Radio Noise for AC Line Converted to DC

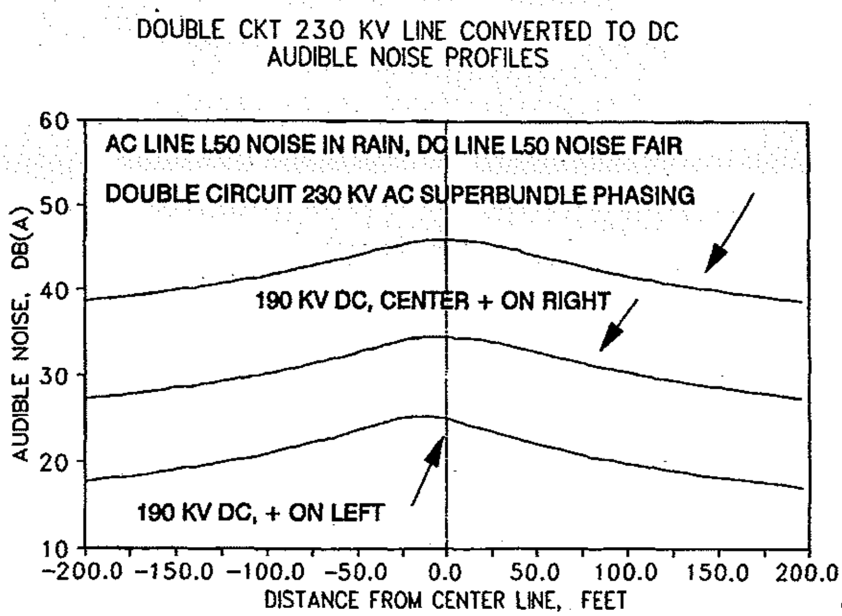

Figure 10.16 Audible Noise for AC Line Converted to DC

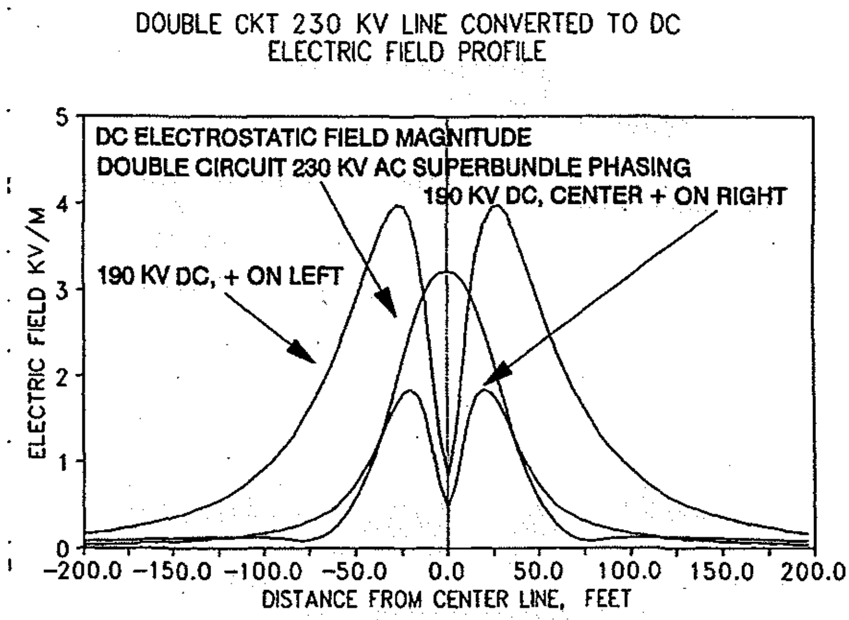

Figure 10.17 Absolute Value of Electric Field for AC Line Converted to DC

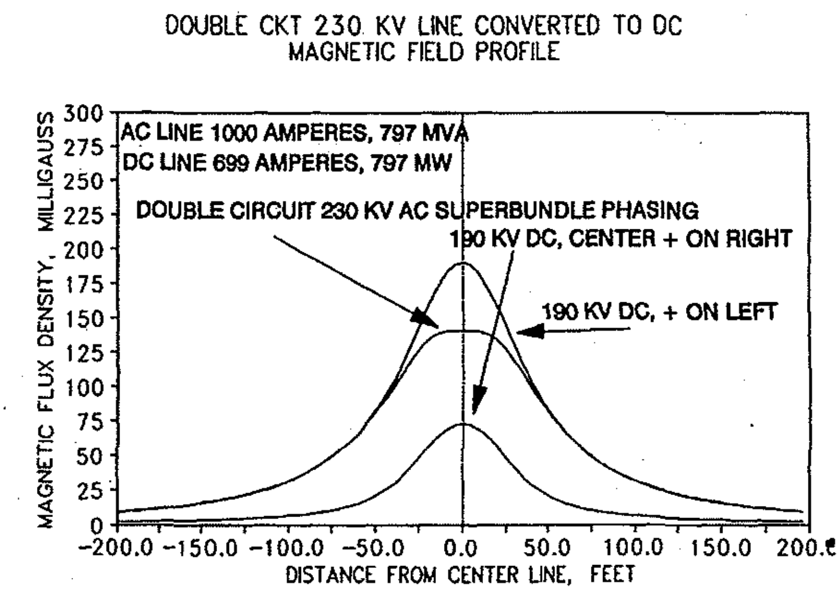

Figure 10.18 Magnetic Field for AC Line Converted to DC, Same MW

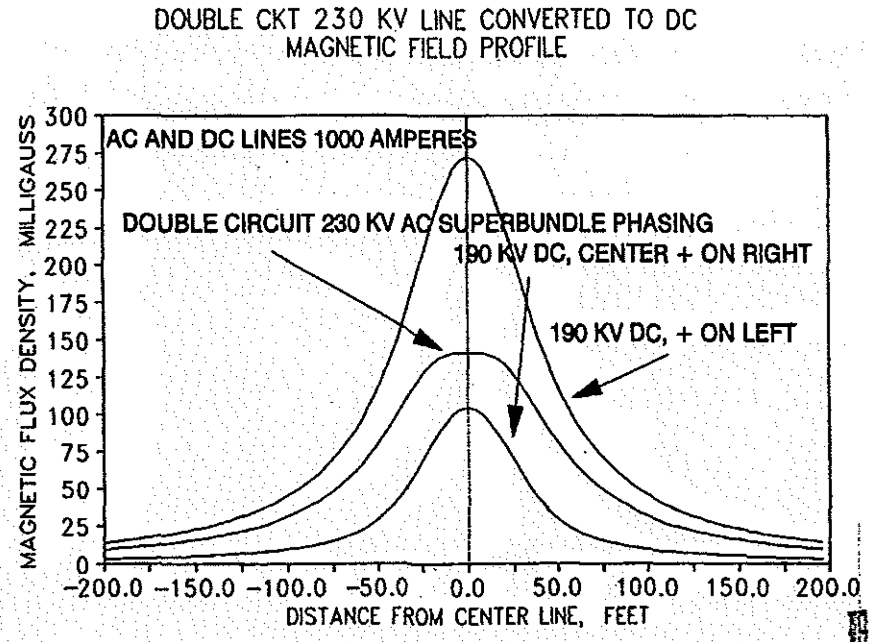

Figure 10.19 Magnetic Field for AC Line Converted to DC, Same Current

10.8 SUMMARY

HVDC systems environmentally are often more compatible than comparable ac systems. HVDC lines produce static electric and magnetic fields which are incapable of inducing voltages and currents on nearby objects by capacitive and inductive coupling. In contrast, capacitively and inductively coupled voltages and currents are primary effects from ac lines.

One environmental factor from dc lines that is not present from ac lines is the migration of air ions away from the line. While dc lines can induce voltage and current as a result of the ion flow in the air surrounding the line, they are incapable of sustaining sufficient steady current to be perceived by a person.

When dc and ac transmission lines are installed on the same structure or right-of-way, consideration must be given to possible human perception of the combined dc and ac electric fields, as human sensitivity to combined fields is greater than to either alone.

Audible and radio noise from a dc line are generally greatest during fair weather, as opposed to audible and radio noise from ac lines which are greatest during foul weather. The maximum noise from a dc line in fair weather is less than the maximum noise from an ac line during foul weather. Audible and radio noise thus may have less of an overall impact from dc transmission lines than from ac lines.

11. BIBLIOGRAPHY

11.1 BIOLOGICAL ENVIRONMENTAL EFFECTS

Albrechtsen, O; Clausen V; Christensen FG; Jensen JG; Moller T. The influence of small atmospheric ions on human well-being and mental performance. International Journal of Biometeorology. 22:249-262, 1978.

Albrechtsen O; Osterballe O; Weeke B. Influence of small atmospheric ions on the airways in patients with bronchial asthma. Symposium on Indoor Climate. 25:377-393, 1979.

American Conference of Governmental Industrial Hygienists (ACGIH). Threshold Limit Values for Chemical Substances and Physical Agents 1991-1992. Cincinnati, OH. 1991.

American Conference of Governmental Industrial Hygienists (ACGIH). Threshold Limit Values for Chemical Substances and Physical Agents 1995-1996. Cincinnati, OH. 1995.

Andersen, I. Effects of natural and artificially generated air ions on mammals. International Journal of Biometeorology. 5:229-38, 1972.

Andersen, I. Mucocilary Function in Trachea Exposed to Ionized and Non-ionized Air. Thesis. Akademisk Boghandel. Arhus, Denmark. 1971.

Angell, RF; Scott, MR; Raleigh, RJ; Bracken, TD. Effects of high voltage direct current transmission lines on beef cattle production. Bioelectromagnetics. 11:273-383, 1990.

Bachman, CH; McDonald, RD; Lorenz, PJ. Some physiological effects of measured air ions. International Journal of Biometeorology. 9:127-39, 1965.

Bachman, CH; McDonald, RD; Lorenz, PJ. Peak changes in electrocardiograms of rats exposed to ionized air. International Journal of Biometeorology. 10:101-06, 1966.

Badre, R; Guillerm, R; Hee, J; Razouls, C. Etude in vitro de l'effet des ions atmospheriques legers sur l'activite ciliaire de l'epithelium tracheal. Ann Pharmac Franc. 24:469-78, 1966.

Bailey, WH; Bissell, M; Brambi, RM; Dorn, CR; Hoppel, WA; Sheppard, AR; Stebbings, JH. A Health & Safety Evaluation of the +/-400 KV DC Powerline. Minnesota Environmental Quality Board, December, 1982.

Bailey, WH; Charry, JM. Behavioral monitoring of rats during exposure to air ions and dc electric fields. Bioelectromagnetics. 7:329-339, 1986.

Bailey, WH; Charry, JM. Acute exposure of rats to air ions: effects on the regional concentration and utilization of serotonin in brain. Bioelectromagnetics. 8:173-181,1987.

Banks, RS; McConnon, D. High voltage direct-current transmission lines: a public health hazard? In: Interaction of Biological Systems with Static Magnetic Fields. Anderson et al (eds). Springfield, VA: NTIS, pp. 67-87, 1987.

Banks, RS; Kannianinen, CM; Clark, RD. Public Health and Safety Effects of High-Voltage Overhead Transmission Lines: An Analysis for the Minnesota Environmental Quality Board. Minneapolis, MN: Minnesota Department of Health. 1977.

Banks, RS; Williams, AN. The Public Health Implication of HVDC Transmission Lines: An Assessment of the Available Evidence. Institute of Electrical and Electronics Engineers. 1983.

Baron, RA. Effects of negative ions on interpersonal attraction: evidence for intensification. Journal of Personality and Social Psychology. 52:547-53, 1987.

Baron, R; Russell, G; Arms, R. Negative ions and behavior: Impact on mood, memory, and aggression among type A and type B persons. Journal of Personality and Social Psychology. 48:746-754, 1985.

Barregard, L; Jarvholm, B; Ungethum, E. Cancer among workers exposed to strong magnetic fields [letter]. The Lancet. 2:892, 1985.

Barron, CI; Dreher, JJ. Effects of electric fields and negative ion concentrations on test pilots. Aerospace Medicine. 35:20-23, 1964.

Bauer, FJ. Effects of ionized air and electroconvulsive shock on learning and innate behavior in rats. Psychological Monographs, General and Applied. 69:1-19, 1955.

Beardwood, CJ; Jordi, P; Abrahams, A. Alterations in rat flexor withdrawal reflex response to a noxious stimulus after exposure to atmospheric ions. In: Anderson, LE; Kelman, BJ; Weigel, RJ (eds). Interaction of Biological Systems with Static and ELF Electric and Magnetic Fields. Richland, WA: Pacific Northwest Laboratory. pp. 29-38, 1987.

Ben-Dov, I; Amirav, I; Shochina, M; Amitai, I; Bar-Yishay, E; Godfrey, S. Effect of negative ionization of inspired air on the response of asthmatic children to exercise and inhaled histamine. Thorax. 38:584-588, 1983.

Bertaccini, G; Baronio, G; Ambrosoli, S. Effects of administering fluid on urinary excretion of 5-hydroxyindoleacetic acid in man. Lancet. 1:1450-57, 1964.

Biggio, G; Piccard, MP; Porceddu, ML; Gessa, GL. Changes in gastro-intestinal serotonin content associated with fasting and satiation. Experiential. 33:745-56, 1977.

Blackman, CF; Blanchard, JP; Benane, SG; House, DE. Empirical tests of an ion parametric resonance model for magnetic field interactions with PC-12 cells. Bioelectromagnetics. 15:239-60, 1994.

Blackman, CF; Most, B. A scheme for incorporating DC magnetic fields into epidemiological studies of EMF exposure. Bioelectromagnetics. 14:413-31, 1993.

Blakemore, RP. Magnetotactic bacteria. Science. 190:377-79, 1975.

Blanchard, JP; Blackman, CF; House, DE. Reinterpretation of whole animal data using the ion parametric resonance model (meeting abstract). 16th Annual Meeting of the Bioelectromagnetics Society, June 12-17, Copenhagen, Denmark, 1994.

Blumstein, GI; Spiegelman, J; Kimbel, P. Atmospheric ionization in allergic respiratory diseases: a double blind study. Archives of Environmental Health. 8:818-19, 1964.

Bowman, JD; Thomas, DC; London, SJ; Peters, JM. Hypothesis: the Risk of Childhood Leukemia May Be Related to Combinations of Power-frequency and Static Magnetic Fields. National Institute of Occupational Safety and Health. 1994.

Breger, L; Blumenthal, NC. Electromagnetic field enhancement of membrane ion transport (meeting abstract). First World Congress for Electricity and Magnetism in Biology and Medicine. Lake Buena Vista, Florida. June 14-19, 1992.

Brown, GC; Kirk, RE. Geophysical variables and behavior: XXXVIII. Effects of ionized air on the performance of a vigilance task. Perceptual and Motor Skills. 64:951-962, 1987.

Budinger, TF. Emerging nuclear magnetic resonance technologie. Annals of the Academy of Sciences. 649:1-18, 1992.

Casper, BM; Wellstone, PD. Powerline - The First Battle of America's Energy War. Amherst, MA: University of Massachusetts Press, 1981.

Cassiano, O; Troncome, S; Carta, Q. Electric fields: some neurovegetative responses in man. Clinical Research. Volume 24. 1965.

Chandra, S; Stefani, S. Effect of constant and alternating magnetic fields on tumor cells *in vitro* and *in vivo*. Hanford Life Sciences Symposium, 18th Annual Meeting, Richland, WA, pp. 436-46, 1979.

Charry, JM. Biological effects of air ions: A comprehensive review of laboratory and clinical data. In: Air Ions: Physical and Biological Aspects. Charry, JM; Kavet, RI (eds). Boca Raton, FL: CRC Press, 1987.

Charry, JM; Bailey, WH. Regional turnover of norepinephrine and dopamine in rat brain following acute exposure to air ions. Bioelectromagnetics. 6:415-425, 1985.

Charry, JM; Bailey, WH; Shapiro, MH; Weiss, JM. Ion exposure chambers for small animals. Bioelectromagnetics. 7:1-11, 1986.

Charry, JM; Hawkinshire, FBW. Effects of atmospheric electricity of some substrates of disordered social behavior. Journal of Personality and Social Psychology. 41:185-187, 1981.

Chiles, WD; Cleveland, MJ; Fox, RE. A Study of the Effects of Ionized Air on Behavior. WADD Technical Report No. 60: 598. November, 1960.

Cooke, P; Morris, PG. The effects of NMR exposure on living organisms. II. A genetic study of human lymphocytes. British Journal of Radiology. 54:446-459, 1981.

Creim, JA; Lovely, RJ; Weigel, WC; Forsythe, WC; Anderson, LE. Failure to produce taste-aversion learning in rats exposed to static electric fields and air ions. Bioelectromagnetics. 16:301-06, 1995.

Creim, JA; Lovely, RJ; Weigel, WC; Forsythe, WC; Anderson, LE. Rats avoid exposure to HVDC electric fields: a dose response study. Bioelectromagnetics. 14:341-52, 1993.

Dabrowska, B; Niedziela, I; Lenkiewicz, Z. The effect of negative ionization on emotional behavior in the mouse (Mus-Musculus L) in the open-field test. Acta Biologica Cracoviensia Series Zoologia. 32:1-15, 1991.

Davis, HP; Mizumori, SJY; Allen, H; Rosenzweig, MR; Bennett, EL; Tenforde, TS. Behavioral studies with mice exposed to dc and 60-Hz magnetic fields. Bioelectromagnetics. 5:147-164, 1984.

Deleanu, M; Stamatiu, C. Influence of aeroionotherapy on some psychiatric symptoms. International Journal of Biometeorology. 29:91-96, 1985.

DeLorge, J. Effects of magnetic fields on behavior in nonhuman primates (meeting abstract). Biomagnetic Effects Workshop, April 6-7, Lawrence Berkeley Lab, University of California, Berkeley, CA. 1978.

Dessauer, F. Zehn Jahre Froschung auf dem Physitzalisch - Medizinischen Grenzgelbeit. Leipzig: Georg Thieme. 1931.

Diamond, MC; Connor, JR; Orenberg, EK; Bissell, M; Yost, M; Krueger, A. Environmental influences on serotonin and cyclic nucleotides in rat cerebral cortex. Science. 210:652-654, 1980.

Dowdall M; DeMontigny C. Effect of atmospheric ions on hippocampal pyramidal neuron responsiveness to serotonin. Brain Research. 342:103-109, 1985.

Droppo, JG. Ozone field studies adjacent to a high-voltage direct-current test line. In: Biological Effects of Extremely Low-Frequency Electromagnetic Fields. Phillips et al (eds). Springfield, VA: National Technical Information Service, CONF-78-10-16, pp. 501-29, 1979.

D'Souza, L; Reno, VR; Nutini, LG; Cook, ES. The effects of a magnetic field on DNA synthesis by ascites sarcoma 37 cells. In: Biological Effects of Magnetic Fields, Volume 2. Barnothy, MF (ed). New York: Plenum Press, 1969.

Durney, CH; Kaminski, M; Anderson, AA; Bruckner-Lea, C; Janata, J; Rappaport, C. Investigation of ac-dc magnetic field effects in planar phospholipid bilayers. Bioelectromagnetics. 13:19-33, 1992.

Durney, CH; Rushforth, CK; Anderson, AA. Resonant AC-DC magnetic fields: Calculated response. Bioelectromagnetics. 9:315-336, 1988.

Eisele, FL. Identification of Ions Near HVDC Transmission Lines. Palo Alto, CA: Electric Power Research Institute (EPRI). Report EN-6391. May, 1989.

Elster, J; Geitel, H. Uber die existenz electoscher ionen in der atmosphare. Terr Mag. 4:213, 1899.

Endo, OM; Nakayama, Y; Itaku, Y; Nishiyama, F. Biological Effects of Ultra High Voltage Transmission Lines - A Preliminary Investigation of Wheat (CRIEPI Report). Japan Central Research Institute of the Electric Power Industry. 1979.

Erban, L. A study of biochemical and hematological changes under the application of ionized air. International Journal of Biometeorology. 3:1-9, 1959.

Falkenberg V; Kirk RE. Effects of ionized air on early acquisition of sidman avoidance behavior by rats. Psychological Reports. 41:1071-1074, 1977.

Fam, WZ. Prolonged exposure of mice to 340 kV/m electrostatic field. IEEE Transactions in Biomedical Engineering. 28:453-459, 1981.

Feychting, M; Ahlbom, A. Magnetic Fields and Cancer in People Residing Near Swedish High Voltage Power Lines. Institute for Miljömedicin, Karolinska Institutet, Stockholm, June, 1992.

Fischer, G. Die bioklimatiogische bedeutung des electrostatischen gleichfeledes. (The bioclimatiological importance of the constant electrostatic field.) Abl. Bak. Hyg. I. Abt. Orig. 157:115-130, 1973.

Fornof, KT; Gilbert GO. Stress and physiological, behavioral, and performance patterns of children under varied air ion levels. International Journal of Biometeorology. 32:260-270, 1988.

Frazier, ME; Andrews, TK; Thompson, BB. In vitro evaluations of static magnetic fields. Biological Effects of Extremely Low Frequency Electromagnetic Fields. Phillips, RD; Gillis, MF; Kaune, WT; Mahlum, DD; Eds. CONF 781016, NTIS, Springfield, VA. pp 417-435, 1979.

Galt, S; Sandblom, J; Hamnerius, Y; Höjevik, P; Saalman, E; Nordén, B. Experimental search for combined AC and DC magnetic field effects on ion channels. Bioelectromagnetics. 14:315-327, 1993.

Genereux, JP; Genereux, MM. Perceptions of Landowners about the Effects of the UPA/CPA Powerline on Human and Animal Health in West Central Minnesota. St. Paul, MN: Minnesota Environmental Quality Board. 1980.

Giannini, AJ; Jones, BT; Loiselle, RH. Reversibility of serotonin irritation syndrome with atmospheric ions. Journal of Clinical Psychiatry. 47:3, 1986.

Gilbert, GO. Effect of negative air ions upon emotionality and brain serotonin levels in isolated rats. International Journal of Biometeorology. 17:267-275, 1973.

Goheen, SC; Bissell, MG; Rao, GA; Larkin, EC. Destruction of human hemoglobin in the presence of water and negative air ions generated by corona discharge. International Journal of Biometeorology. 29:353-59, 1985.

Goheen, SC; Larkin, EC; Bissell, MG. Oxone produced by corona discharge in the presence of water. International Journal of Biometeorology. 28:157-61, 1983.

Griffith, DB. Selected Biological Parameters Associated with a 400 +/- kV dc Transmission Line in Oregon. Portland, OR: Bonneville Power Administration. 1977.

Gromyko, NM; Krivodaeva, OL. Features of the behavioral reactions of rats during exposure to constant electrical fields of varied intensities. Neuroscience and Behavioral Physiology. 22:419-22, 1992.

Grundler, W; Kaiser, F; Keilmann, F; Walleczek, J. Mechanisms of electromagnetic interaction with cellular systems. Naturwissenschaften. 79:551-559, 1992.

Guillerm, R; Badre, R; Hee, J; Razouls, C. Effets des ions legers atmospheriques sur l'activite ciliaire de la mugueuse tracheale do mouton et de Lapin in vitro. Comptes Rendus Acad Sci. 262:669-71, 1966.

Halcomb CG ; Kirk RE. Effects of air ionization upon the performance of a vigilance task. Journal of Engineering Psychology. 4:120-126, 1965.

Halle, B. On the cyclotron resonance mechanism for magnetic field effects on transmembrane ion conductivity. Bioelectromagnetics. 9:381-385, 1988.

Halpern, MH; Greene, AE. Effects of magnetic fields on growth of HeLa cells in tissue culture. Nature. 202:717, 1964.

Hawkins LH. The influence of air ions, temperature and humidity on subjective well being and comfort. Journal of Environmental Psychology. 1:279-292, 1981.

Hawkins LH; Barker T. Air ions and human performance. Ergonomics. 21:273-278, 1978.

Hedge A; Collis MD. Do negative air ions affect human mood and performance? Annals of Occupational Hygiene. 31:285-290, 1987.

Herrington, LP. The influence of ionized air upon normal subjects. Journal Clinical of Investigation. 14:70-80, 1935.

Herrington, LP; Kuh, C. The reaction of hypertensive patients to atmospheres containing high concentrations of heavy ions. Journal of Industrial Hygiene and Toxicology. 20:179-87, 1938.

Hinsull, SM. The effect of long-term exposure to negative air ions on the growth and life-span of laboratory rats. Journal of Clinical and Experimental Gerontology. 10:1-12, 1988.

Hinsull, SM; Head, EL. The effect of positive air ions on reproduction and growth in laboratory rats. International Journal of Biometeorology. 30:69-75, 1986.

Hinsull, SM; Bellamy, D; Head, EL. Effects of air ions on the neonatal growth of laboratory rats. International Journal of Biometeorology. 25:323-327, 1981.

Hinsull SM; Bellamy D; Head, EL. The effect of negative air ionization on the growth of four generations of laboratory rats. International Journal of Biometeorology. 28:163-168, 1984.

Hiroaka, M; Miyakoshi, J; Li, YP; Shung, B; Takebe, H; Abe, M. Induction of c-FOS gene expression by exposure to a static magnetic field in HeLaS3 cells. Cancer Research. 52:6522-24, 1992.

Hjeresen, DL; Kaune, WT; Decker, JR; Phillips, RD. Effects of 60-Hz fields on avoidance behavior and activity of rats. Bioelectromagnetics. 1:299-312, 1980.

Hong, FT. Photoelectric and magneto-orientation effects in pigmented biological membranes. Journal of Colloid and Interface Science. 58:471-97, 1977.

Hoppel, WA. Study of Drifting, Charged Aerosols from HVDC Lines. Final Report. Palo Alto: Electric Power Research Institute (EPRI). Report No EL-1327. 1980.

Ingham, DB. Precipitation of charged particles in human airways. Journal of Aerosol Science. 12:131-35, 1981.

International Commission on Non-Ionizing Radiation Protection (ICNIRP). Guidelines on limits of exposure to static magnetic fields. Health Physics. 66:100-6, 1994.

Jaskowski, J; Mysliwski, A. Effect of air ions on healing of wounds of rat skin. Experimental Pathology (JENA). 29:113-117, 1986.

Jaskowski J; Witkowski J; Mysliwski A; Zawadzki H. Effect of air ions on L-1210 cells changes in fluorescence of membrane-bound 1, 8-aniline-naphthalene- sulfonate (ANS) after *in vitro* exposure of cells to air ions. General Physiology and Biophysics. 5:511-516, 1986.

Johnson, GB. The electrical environment and HVDC transmission lines. In: Conference on Environmental Ions and Related Biological Effects. Charry, JM (ed). Philadelphia, PA: American Institute of Medical Climatology, pp. 66-82, 1982.

Johnson, GB; Zaffanella, LE. Characterization of the electrical environment beyond the corridor of an HVDC transmission line. DOE/EPRI/NYS Contractor's Review Meeting. Alexandria, VA, November, 1985.

Jones, FC. The Effects of a Positive Electric Field on the Behavior of Emotionally Disturbed Children. University of Kansas. Dissertation No. 75-6137. 1974.

Jordan, J; Sokoloff, B. Air ionization, age and maze learning of rats. Journal of Gerontology. 14:344-348, 1959.

Kellogg, EW; Yost, MG. The effects of long-term air ion and direct current electric field exposures on survival characteristics in female namru mice. Journal of Gerontology. 41:147-153, 1986.

Kellogg, EW; Yost, MG; Reed, EJ; Krueger, AP. Long-term biological effects of air ions and dc electric fields on namru mice: First year report. International Journal of Biometeorology. 29:253-268, 1985. (a)

Kellogg, EW; Yost, MG; Reed, EJ; Madin, SH. Long-term biological effects of air ions and dc electric fields on namru mice: Second Year Report. International Journal of Biometeorology. 29:269-283, 1985. (b)

Kensler, CJ; Battista, SP. Chemical and physical factors affecting mammalian ciliary activity. American Review of Respiratory Disease. 13:93-102, 1966.

Kirschvink, JL; Kobayashi-Kirschvink, A. Magnetite (Fe_3O_4) biomineralization in human tissues: a solution to the thermal noise problem of ELF bioeffects. The First World Congress for Electricity and Magnetism in Biology and Medicine, Buena Vista Palace, Lake Buena Vista, Florida, June 14-19, 1992.

Kirschvink, JL. Birds, bees, and magnetism. Trends in Neurosciences. 5:160-167, 1982.

Konerman, G; Monig, H. Untersuchungen uber den einflub statischer magnetfelder auf die pranatale entwickling der maus (Studies on the influence of static magnetic fields on prenatal development of mice). Radiologie. 26:490-497, 1986.

Koontz; AE; Heath, RL. Ozone alteration of transport of cations and the Na+/K+-ATPase in human erythrocytes. Archives of Biochemistry and Biophysics. 198:493-500, 1979.

Kotaka, S. Effects of air ions on microorganisms and other biological materials. CRC Critical Reviews in Microbiology. 6:109-49, 1978.

Krivova, TI; Lukovkin, VV; Uakubenko, AV. Effect of dc electrical field on the human organism. In: Protection from the action of electromagnetic fields and electric current in industry, Filippo, VI; Morozov, YA(eds.). All-Union Central Scientific Research Institute of Work Safety, Moscow. DOE-TR-20,1973.

Krueger, AP; Andriese PC; Kotaka, S. The biological mechanism of air ion action: The effect of carbon dioxide in inhaled air on the blood level or 5HT in mice. International Journal of Biometeorology. 7:3-16, 1963.

Krueger, AP; Andriese, PC; Kotaka, S. Small air ions: Their effect on blood levels on serotonin in terms of modern physical theory. International Journal of Biometeorology. 12:225-239, 1968.

Krueger, A; Kotaka, S. The effects of air ions on brain levels of serotonin in mice. International Journal of Biometeorology. 13:25-38, 1969.

Krueger, AP; Kotaka, S; Reed, EJ; Turner, S. The effects of air ions on bacterial and viral pneumonia in mice. International Journal of Biometeorology. 14:247-260, 1970.

Krueger, AP; Kotaka, S; Andriese, PC. Studies on the effects of gaseous ions on plant growth. I. The influence of positive and negative ions on the growth of *Avena sativa*. Journal of General Physiology. 45:879-95, 1962.

Krueger, AP; Kotaka, S; Andriese, PC. Studies on air-ion-enhanced iron chlorisis. I. Active and residual iron. International Journal of Biometeorology. 8:5-16, 1964.

Krueger, AP; Levine, HB. The effect of unipolar positively ionized air on the course of Coccidiomycoisis in mice. International Journal of Biometeorology. 11:279-88, 1967.

Krueger, AP; Reed, EJ. Effect of the air ion environment on influenza in the mouse. International Journal of Biometeorology. 16:209-232, 1972.

Krueger, AP; Reed, EJ; Day, MB; Brooke, KA. Further observations on the effect of air ions on influenza in the mouse. International Journal of Biometeorology. 18:46-56, 1974.

Krueger, AP; Smith, RF. Effects of air ions on isolated rabbit trachea. PSEBM. 96:807-09, 1957.

Krueger, AP; Smith, RF. The effects of air ions on the living mammalian trachea. Journal of General Physiology. 42:69-82, 1958.

Krueger, AP; Smith, RF. Parameters of gaseous ion effects on the mammalian trachea. Journal of General Physiology. 42:959-69, 1959.

Krueger, AP; Smith, RF. The biological mechanism of air ion action. I. 5- hydroxytryptamine as the endogenous mediator of positive air effects on the mammalian trachea. Journal of General Physiology. 43:533-40, 1960. (a)

Krueger, AP; Smith, RF. The biological mechanism of air ion action. II. Negative air ion effects on the concentration and metabolism of 5-hydroxytryptamine in the mammalian respiratory tract. Journal of General Physiology.44:269-76, 1960. (b)

Krueger, AP; Smith, RE; Millar, J. Effects of air ions on trachea of primates. PSEBM. 101:506-07, 1959.

Krupa, S; Pratt, GC. UPA/CPA High Voltage Transmission Line Potential Generation of Air Pollutants and Their Impact on Vegetation. University of Minnesota. 1982.

Lambert JF; Olivereau JM. Single-trial passive avoidance learning by rats treated with ionized air. Psychological Reports. 47:1323-1330, 1980.

Lambert JF; Olivereau JM; Tuong-Ngoc A. Influence of artificial air ionization on the electroencephalogram of the awake rat. International Journal of Biometeorology. 25:71-75, 1981.

Lednev, VV. Possible mechanism for the influence of weak magnetic fields on biological systems. Bioelectromagnetics. 12: 71-75, 1991.

Lefcoe, N. Ventilatory function after exposure to ionized air. Archives of Environmental Health. 7:664-67, 1963.

Lenkiewicz Z.; Dabrowski B; Schiffer Z.; The influence of negative ionization of the air on motor activity in Syrian hamsters (Masocricetus auratus Waterhouse) in light conditions. International Journal of Biometeorology. 33:251-258, 1989.

Lerchl, A; Nonaka, KO; Reiter, RJ. Pineal gland "magnetosensitivity" to static magnetic fields is a consequence of induced electric currents (eddy currents). Journal of Pineal Research. 10:109-116, 1991.

Lerchl, A; Nonaka, KO; Stokkan, KA; Reiter, RJ. Marked rapid alterations in nocturnal pineal serotonin metabolism in mice and rats exposed to weak intermittent magnetic fields. Biochemical and Biophysical Research Communication. 169:102-108, 1990.

Liboff, AR; McLeod, BR; Smith, SD. Ion cyclotron resonance effects of ELF fields in biological systems. Extremely Low Frequency Electromagnetic Fields: The Question of Cancer. Wilson, BW; Stevens, RS; Anderson, LE; (eds). Batelle Press: Columbus, OH., 1990.

Liboff, AR; McLeod, BR. Power lines and the geomagnetic field. Bioelectromagnetics. 16:227-30, 1995.

Lipin I; Gur I; Amitai I; Amitai I; Godfrey S. Effect of positive ionization of inspired air on the response of asthmatic children to exercise. Thorax. 39:594-596, 1984.

London, SJ; Thomas, DC; Bowman, JD; Sobel, E; Cheng, T-C; Peters, JM. Exposure to residential electric and magnetic fields and risk of childhood leukemia. American Journal of Epidemiology. 134:923-37, 1991.

Lott, JR; McCain, HB. Some effects of continuous and pulsating electric fields on brain wave activity in rats. International Journal of Biometeorology. 17:221-25, 1973.

Mahlum, DD; Sikov, MR; Decker, JR. Dominant lethal studies in mice exposed to direct-current magnetic fields. Hanford Life Sciences Symposium, 18th Annual Meeting. Richland, WA. October 16-18, 1979.

Malinin, GI; Gregory, WD; Morelli, L; Sharma, VK; Houck, JC. Evidence of morphological and physiological transformation of mammalian cells by strong magnetic fields. Science. 194:844-846, 1976.

Marsh JL; Armstrong TJ; Jacobson AP; Smith RG. Health effect of occupational exposure to steady magnetic fields. American Industrial Hygiene Association Journal. 43:387, 1982.

Martin, FB; Bender, A; Steuernagel, G; Robinson, RA; Revsbech, R; Sorenson, DK; Williamson, N; Williams, A. An Epidemiologic Study of Holstein Dairy Cow Performance and Reproduction Near a High-Voltage Direct-Current Transmission Line. Minneapolis, MN: University of Minnesota. 1983. (a)

Martin, FB; Steuernagel, G; Bender, A; Robinson, RA; Revsbech, R; Sorenson, DK; Williamson, N. A Statistical/Epidemiological Study of Bovine Performance Associated with the CPA/UPADC PowerLine Minnesota. Final Report. September. 1983. (b)

Mayyasi, AM; Terry, RA. Effects of direct electric fields, noise, sex and age on maze learning in rats. International Journal of Biometeorology. 13:101-11, 1969.

McCann, J; Dietrich, F; Rafferty, C; Martin, A. A critical review of the genotoxic potential of electric and magnetic fields. Mutation Research. 297:61-95, 1993.

McDonald, F. Effect of static magnetic fields on osteoblasts and fibroblasts *in vitro*. Bioelectromagnetics. 14:187-96, 1993.

McDonald, RD; Bachman, CH; Lorenz, PJ. Some physiological effects of air ion treatment without ion inhalation. International Journal of Biometeorology. 9:141-147, 1965.

McDonald RD; Bachman CH; Lorenz PJ. Some psychomotor and physiological tests on humans exposed to air ions. Aerospace Medicine. 38:145-148, 1967.

McGurk, FCJ. Psychological effects of artificially produced air ions. American Journal of Physical Medicine. 38:36-37, 1959.

McLauchlan, KA. Magnetokinetics, mechanistics and synthesis. Chem Brit. September: 895-898, 1989.

McLauchlan, K. Are environmental magnetic fields dangerous? Physics World. 5:41-45 1992.

McLeod, BR; Liboff, AR. Dynamic characteristics of membrane ions in multifield configurations of low-frequency electromagnetic radiation. Bioelectromagnetics. 7:177-189, 1986.

McLeod, BR; Smith, SD; Liboff, AR. Calcium and potassium cyclotron resonance curves and harmonics in diatoms (*A. coffeaeformis*). Journal of Bioelectricity. 6:153-168, 1987. (a)

McLeod, BR; Smith, SD; Cooksey, KE; Liboff, AR. Ion cyclotron resonance frequencies enhance Ca^{++} dependent mobility in diatoms. J. Bioelectricity. 6: 1-12, 1987. (b).

Melandri, C; Prodi, V; Tarroni, G; Formingnani, M; DeZaiacom, T; Bompane, GF; Maestri, G; Giacomelli, G; Maltoni, G. On the deposition of unipolarly charged particles in the human respiratory tract. In: Inhaled Particles IV, Part I. Walton, WH; McGovern, B (eds). Oxford: Pergamon Press, pp. 193-200, 1977.

Milham, S. Mortality in aluminum reduction plant workers. Journal of Occupational Medicine. 21:475-480, 1979.

Minkh, AA. The effect of ionized air on work capacity and vitamin metabolism. Proceedings of the International Conference on the Ionization of the Air. Philadelphia. 1961.

Mose ,JR; Fischer, G. Zur wirkung electrostaischer leichfelder, wieteretier excpenmentelle ergebnisse. (Effect of electrostatic fields: results or further animal experiments). Arch. Hyg. Bakeriol. 154:378-386, 1970.

Motley HL; Yanda, R. Environmental air pollution, emphysema and ionized air on psychiatric patients. Diseases of the Chest. 50:343-352, 1966.

Mur, JM; Moulin, JJ; Meyer-Bisch, C; Massin, N; Coulon, JP; Loulergue, J. Mortality of aluminum reduction plant workers in France. International Journal of Epidemiology. 16:257-64, 1987.

National Radiological Protection Board (NRPB). Board statement on restrictions on human exposure to static and time varying electromagnetic fields and radiation. Documents of the NRPB. Volume 4, Number 5. 1993.

Nolfi, JR; Haupt, RC. Effects of High Voltage Power Lines on Health: Results from a Systematic Survey of a Population along the 400 kV dc Pacific Intertie. Associates in Rural Development, Inc., January 29, 1982.

Olcese, J. The neurobiology of magnetic field detection in rodents. Progress in Neurobiology. 35:325-330, 1990.

Olcese, J; Reuss, S; Stehle, J; Steinlechner, S; Vollrath, L. Responses of the mammalian retina to experimental alteration of the ambient magnetic field. Brain Research. 448:325-330, 1988.

Olcese, J; Reuss, S; Vollrath, L. Evidence for the involvement of the visual system in mediating magnetic field effects on pineal melatonin synthesis in the rat. Brain Research. 333:382-384, 1985.

Olivereau, JM. Action des ions atmospheriques positifs sur le complexe hypothalamo-hypophysaire et la regulation du metabolisme hyro-mineral chez le rat albinos. Zeitschrift fuer Zellforschung und Mikroskopische Anatomie. 107:361-73, 1970. (a)

Olivereau, JM. Comportement de souns soumises a' un stimulus thermique algogene apres traitment aix ions atmospheniques positifs. Comptes Rendus des Seances de la Societe de Biologie et de ses Filiales. 164:501-05, 1970. (b)

Olivereau, JM. Influence of atmospheric ions on the activity or albino rats. Comptes Rendus des Seances de la Societe de Biologie et de ses Filiales. 164:950-962, 1970.(c)

Olivereau, JM; Lambert, JF; Truong-Ngoc, A. Influence of air ions on brain activity induced by electrical stimulation in the rat. International Journal of Biometeorology.25:63-69, 1981.

Olivereau JM; Lambert JF. Effects of air ions on some aspects of learning and memory of rats and mice. International Journal of Biometeorology. 25:53-62, 1981.

Olsen, JH; Nielson, A; Schlugen, G. Residence near high voltage facilities and risk of cancer in children. British Medical Journal. 307:891-895, 1993.

Parkinson, WC; Sulik, GL. Diatom response to extremely low-frequency magnetic fields. Radiation Research. 130:319-330, 1992.

Pavlik, I. The fate of light air ions in the respiratory pathways. International Journal of Biometeorology. 11:175-85, 1967.

Peteiro-Cartelle, FJ; Cabezas-Cerrato, J. Absence of kinetic and cytogenetic effects on human lymphocytes exposed to static magnetic fields. Journal of Bioelectricity. 8:11-20, 1989.

Prasad, AV; Miller, MW; Carstensen, EL; Cox, C; Azadniv, M; Brayman, AA. Failure to reproduce increased calcium uptake in human lymphocytes at purported cyclotron resonance exposure conditions. Radiation and Environmental Biophysics. 30:305-320, 1991.

Public Utility Commission of Texas (PUCT). Application of CP&L, HL&P, and SWEPCO for a + 400 kV HVdc Transmission Line form Walker County Station South to the Matagorda Station at the South Texas Project. Docket No 5023. Austin, TX. 1984.

Raleigh, RJ. Joint HVDC Agricultural Study: Final Report. Portland, OR: Bonneville Power Administration, 1988.

Reese, JA; Frazier, ME; Morris, JE; Buschbom, RL; Miller, DL. Evaluation of changes in diatom mobility after exposure to 16-Hz electromagnetic fields. Bioelectromagnetics. 12: 21-25, 1991.

Reiter, RJ; Richardson, BA; Yaga, K; Manchester, LC; Golovko, D; Abdelsalami, M. Pulsed static and magnetic field effects on pineal serotonin metabolism: *in vivo* and *in vitro* studies (meeting abstract). Annual Review of Research on Biological Effects of 50 and 60 Hz Electric and Magnetic Fields, November 3-7, Milwaukee, WI. 1991.

Reuss, ST; Semm, P; Vollrath, L. Different types of magnetically sensitive cells in the pineal gland. Neuroscience Letters. 40:23-26, 1983.

Reuss, S; Olcese, J. Magnetic field effects on the rat pineal gland: role of retinal activation by light. Neuroscience Letters. 64:97-101, 1986.

Rockette, HE; Arena, VC. Mortality studies of aluminum reduction plant workers: potroom and carbon department. Journal of Occupational Medicine. 25:549-557, 1983.

Sandler, PJ; Meghji, S; Murray, AM; Sandy, JR; Crow, V; Reed, T. Magnets and orthodontics. British Journal of Orthodontics. 16:243-249, 1989.

Sandweiss, J. On the cyclotron resonance model of ion transport. Bioelectromagnetics. 11:203-205, 1990.

Sato, K; Yamagucci, H; Miyamoto, H; Kinouchi, Y. Growth of human cultured cells exposed to a non-homogeneous static magnetic field generated by Sm-Co magnets. Biochimica et Biophysica Acta. 1136:231-238, 1992.

Savitz, DA; Wachtel, H; Barnes, FA; John, EM; Tvrdik, JG. Case-control study of childhood cancer and exposure to 60-hertz magnetic fields. American Journal of Epidemiology. 128:21-38, 1988.

Semm, P; Schneider, T; Vollrath, L. Effects of an Earth-strength magnetic field on electrical activity of pineal cells. Nature. 288:607, 1980.

Sigel, S. Bio-psychological Influences of Air Ions in Men: Effects on 5Ht and Mood. Ph.D Thesis, University of California, San Francisco, University Microfilms No. 7918206. 1979.

Sikov, MR; Mahlum, DD; Montgomery, LD; Decker, JR. Development of mice after intrauterine exposure to direct current magnetic fields. In: Biological Effects of Extremely Low Frequency Electromagnetic Fields. Phillips, RD; Gillis, MF; Kaune, WT; Mahlum, DD (eds). Washington, D.C.; U.S. Department of Energy; 462-473, 1979.

Silverman, D; Kornblueh, IH. Effect of artificial ionization of the air on electroencephalogram. American Journal of Physical Medicine. 36:352-358, 1957.

Slote, L. An experimental evaluation of man's reaction to an ionized air environment. Proceedings of the International Conference on the Ionization of the Air, Vol. 2. American Institute or Medical Climatology, Philadelphia, 1961.

Smith, SD; McLeod, BR; Liboff, AR; Cooksey, K. Calcium cyclotron resonance and diatom motility. Bioelectromagnetics. 8:215-227, 1987. (a)

Smith, SD; McLeod, BR; Liboff, AR; Cocksey, KE. Calcium cyclotron resonance and diatom motility. Studia Biophysica. 119:131-136, 1987. (b)

Stehle, J; Reuss, S; Schroder, H; Henschel, M; Vollrath, L. Magnetic field effects on pineal n-acetyltranfersferase activity and melatonin content in the gerbil--role of pigmentation and sex. Physiology and Behavior. 44:91-94, 1988.

Sulman FG; Danon A; Pfeifer Y; Tale E; Weller, CP. Urinalysis of patients suffering from climatic heat stress (Sharav). International Journal of Biometeorology. 14:45-53, 1970.

Sulman FG; Levy D; Lunkan L; Pfeifer Y; Tal, E. Absence of harmful effects of protracted negative air ionization. International Journal of Biometeorology. 22:53-58, 1978.

Sulman FG; Levy D; Pfeifer Y; Superstine E ; Tal, E. Effects of the Sharav and Bora on urinary neurohormone excretion in 500 weather sensitive females. International Journal of Biometeorology. 19:202-204, 1975.

Swanson, J. Measurements of static magnetic fields in homes in the UK and their implication for epidemiological studies of exposure to alternating magnetic fields. Journal of Radiological Protection. 14:67-75, 1994.

Takatsuji, T; Sasaki, MS; Takekoshi, H. Effect of static magnetic field on the induction of chromosome aberrations by 4.9 MEV protons and 23 MEV alpha particles. Journal of Radiation Research (Tokyo). 30:238-246, 1989.

Tenforde, TS. Magnetic Field Applications in Modern Technology and Medicine. NTIS Document No. DE85015197/XAB. 1985.

Terry, RA; Harden, DC; Mayyasi, AM. Effects of negative air ions, noise, sex, and age on maze learning in rats. International Journal of Biometeorology. 13:39-49, 1969.

Tom, G; Poole, MF; Galla, J; Berrier, J. The influence of negative ions on human performance and mood. Human Factors. 23:633-636, 1981.

U.S. Environmental Protection Agency. Health Effects Summary Tables: FY-1994 Annual. Washington, DC; Office of Research and Development. EPA 540-R-94-020. March, 1994.

Verkasalo, PK; Pukkala, E; Hongisto, MY; Valjus, JE; Järvinen, PJ; Heikkilä, KV; Koskenvuo, M. Risk of cancer in Finnish children living close to power lines. British Medical Journal. 307:895-899, 1993.

Wachter, SL; Widmer, RE. The effects of negative air ions on plant growth. Horticultural Science. 11:576-78, 1976.

Warner, RRP. Current status and implication of serotonin in clinical medicine. In: Advances in Internal Medicine. Dock, W; Snapper, I (eds). Chicago: Yearbook Medical Publishers, Inc. 1967.

Wertheimer, N; Leeper, E. Electrical wiring configurations and childhood cancer. American Journal of Epidemiology. 109:273-284, 1979.

Witkowski, JM; Mysliwski, A. Effect of air ions on the membrane Na. K-ATPase activity of L 1210 cells. General Physiology and Biophysics. 5:505-510, 1986.

Wolff, S; Crooks, LE; Brown, P; Howard, R; Painter, RB. Tests for DNA and chromosomal damage induced by nuclear magnetic resonance imaging. Radiology. 136:707-710, 1980.

Wong, PS; Sastre, A. Simultaneous AC and DC magnetic field measurements in residential areas: implications for resonance theories of biological effects. IEEE Transactions on Power Delivery. 10:1906-12, 1995.

Yaga, K; Reiter, RJ; Manchester, LC; Nieves, H; Sun, JH; Chen, LD. Pineal sensitivity to pulsed static magnetic fields changes during the photoperiod. Brain Research Bulletin. 30:153-56, 1993.

Yaglou, CP. Are air ions a neglected biological factor? In: The Air We Breathe. Farber, SM; Wilson, RHL (eds). Springfield, IL: Thomas, pp. 269-80, 1961.

Yaglou CP; Brandt AD; Benjamin, LC. Observations on a group of subjects before, during and after exposure to ionized air. Journal of Industrial Hygiene. 15:341-353, 1933.

Yates, A; Gray, F; Beutler, LE; Sherman, DE; Segerstrom, EM. Effect of negative air ionization on hyperactive and autistic children. American Journal of Physical Medicine. 66:264-268, 1987.

Zybelberg, B; Loveless, MH. Preliminary experiments with ionized air in asthma. Journal of Asthma. 31:370-74, 1960.

11.2 ELECTRICAL ENVIRONMENTAL EFFECTS

Technical Papers

Audible, Radio and Television Noise

F. S. Prabhakara and I. Vancers, "AN, RI and TVI Performance of Square Butte HVDC Line," IEEE conference paper A 78 585-2 presented at the IEEE/PES Summer Meeting, Los Angeles, CA, July 16-21, 1978.

G. B. Johnson, "Insect Deposition on HVDC Lines," paper presented to the IEEE DC Fields and Ions Working Group, July 20, 1982.

M. Fukushima, K. Tanabe and Y. Nakano, "Prediction Method and Subjective Evaluation of Audible Noise Based on Results at the Shiobara HVDC Test Line," IEEE Transactions on Power Delivery, Vol. 2, No. 4, October, 1987, p 1170.

M. Yasui, Y. Takahashi, A. Takenaka, K. Naito, Y. Hasegawa and K. Kato, "RI, TVI and AN Characteristics of HVDC Insulator Assemblies Under Contaminated Condition," IEEE Transactions on Power Delivery, Vol. 3, No. 4, October, 1988, p 1913.

P. S. Maruvada, R. D. Dallaire, O. C. Norris-Elye, C. V. Thio and J. S. Goodman, "Environmental Effects of the Nelson River HVDC Transmission Lines - RI, AN, Electric Field, Induced Voltage, and Ion Current Distribution Tests," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No. 4, April, 1982, p 951.

R. D. Dallaire, P. S. Maruvada and N. Rivest, "HVDC Monopolar and Bipolar Cage Studies on the Corona Performance of Conductor Bundles," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-103, No. 1, January, 1984, p 84.

R. D. Dallaire and P. S. Maruvada, "Corona Performance of a +/- 400 kV Bipolar DC Transmission Line Configuration," IEEE Transactions on Power Delivery, Vol. 2, No. 2, April, 1987, p 477.

T. Fujimura, K. Naito, R. Matsuoka and Y. Suzuki, "A Laboratory Study on RI, TVI and AN of Insulator Strings for DC Transmission Line Under Contaminated Condition." IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No. 4, April, 1982, p 815.

T. Suda, Y. Hirayama and Y. Sunaga, "Aging Effects of Conductor Surface Conditions on DC Corona Characteristics," IEEE Transactions on Power Delivery, Vol. 3, No. 4, October, 1988, p 1903.

V. L. Chartier and R. D. Stearns, "Examination of Grizzly Mountain Data Base to Determine Effects of Relative Air Density and Conductor Temperature on HVDC Corona Phenomena," IEEE Transactions on Power Delivery, Vol. 5, No. 3, July, 1990, p 1575.

Y. Sunaga and Y. Sawada, "Method of Calculating Ionized Field of HVDC Transmission Lines and Analysis of Space Charge Effects on RI," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-99, No. 2, March/April, 1980, p 605.

Coupled Voltages on Objects at Ground Level

P. S. Maruvada, R. D. Dallaire, O. C. Norris-Elye, C. V. Thio and J. S. Goodman, "Environmental Effects of the Nelson River HVDC Transmission Lines - RI, AN, Electric Field, Induced Voltage, and Ion Current Distribution Tests," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No. 4, April, 1982, p 951.

Y. Sunaga, Y. Amano and T. Sugimoto, "Electric Field and Ion Current at the Ground and Voltage of Charged Objects Under HVDC Lines," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No. 4, April, 1981, p 2082.

Electric Fields and Ions

"Experimental Evaluation of Instruments for Measuring DC Transmission Line Electric Fields and Ion Currents," IEEE Task Force Report, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-102, No. 11, November, 1983, p 3549.

B. L. Qin, J. N. Sheng and G. Gela, "Accurate Calculation of Ion Flow Field Under HVDC Bipolar Transmission Lines," IEEE Transactions on Power Delivery, Vol. 3, No. 1, January, 1988, p 368.

D. H. Nguyen and P. S. Maruvada, "An Exposure Chamber for Studies on Human Perception of DC Electric Fields and Ions," IEEE Transactions on Power Delivery, Vol. 9, No. 4, October, 1994, p 2037.

E. L. Harris, B. D. Rindall, N. J. Tarko and O. C. Norris-Elye, "The Effect of a Helicopter on DC Fields and Ions," IEEE Transactions on Power Delivery, Vol. 8, No. 4, October, 1993, p 1837.

G. C. Acord and P. D. Pedrow, "Response of Planar and Cylindrical Ion Counters to a Corona Ion Source," IEEE Transactions on Power Delivery, Vol. 4, No. 3, July, 1989, p 1823.

M. G. Comber and G. B. Johnson, "HVDC Field and Ion Effects Research at Project UHV: Results of Electric Field and Ion Current Measurements," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No. 7, July, 1982, p 1998.

M. Hara, N. Hayashi, K. Shiotsuki and M. Akazaki, "Influence of Wind and Conductor Potential on Distributions of Electric Field and Ion Current Density at Ground Level in DC High Voltage Line to Plane Geometry," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No. 4, April, 1982, p 803.

N. Fujioka, Y. Tsunoda, A. Sugimura and K. Arai, "Influence of Humidity on Variation of Ion Mobility With Life Time in Atmospheric Air," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-102, No. 4, April, 1983, p 911.

P. J. Carter and G. B. Johnson, "Space Charge Measurements Downwind from a Monopolar 500 kV HVDC Test Line," IEEE Transactions on Power Delivery, Vol. 3, No. 4, October, 1988, p 2056.

P. S. Maruvada, R. D. Dallaire and R. Pedenault, "Development of Field-Mill Instruments for Ground-Level and Above-Ground Electric Field Measurement Under HVDC Transmission Lines," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-102, No. 3, March, 1983, p 738.

P. S. Maruvada, R. D. Dallaire, O. C. Norris-Elye, C. V. Thio and J. S. Goodman, "Environmental Effects of the Nelson River HVDC Transmission Lines - RI, AN, Electric Field, Induced Voltage, and Ion Current Distribution Tests," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No. 4, April, 1982, p 951.

R. H. McKnight and F. R. Kotter, "A Facility to Produce Uniform Space Charge for Evaluating Ion Measuring Instruments," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-102, No. 7, July, 1983, p 2349.

R. H. McKnight, F. R. Kotter, M. Misakian, "Measurement of Ion Current Density at Ground Level in the Vicinity of High Voltage DC Transmission Lines," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-102, No. 2, April, 1983, p 934.

R. H. McKnight, "The Measurement of Net Space Charge Density Using Air Filtration Methods," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-104, No. 4, April, 1985, p 971.

S. A. Sebo, R. Caldecott and D. G. Kasten, "Model Study of HVDC Electric Field Effects," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No. 6, June, 1982, p 1743.

T. Takuma and T. Kawamoto, "A Very Stable Calculation Method for Ion Flow Field of HVDC Transmission Lines," IEEE Transactions on Power Delivery, Vol. 2, No. 1, January, 1987, p 189.

T. Takuma, T. Ikeda and T. Kawamoto, "Calculation of Ion Flow Fields of HVDC Transmission Lines by the Finite Element Method," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No. 12, December, 1981, p 4802.

T. D. Bracken, A. S. Capon, D. V. Montgomery, "Ground Level Electric Fields and Ion Currents on the Celilo-Sylmar +/- 400 kV DC Intertie During Fair Weather," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-97, No. 2, March/April, 1978, p 370.

T. Suda and Y. Sunaga, "An Experimental Study of Large Ion Density Under the Shiobara HVDC Test Line," IEEE Transactions on Power Delivery, Vol. 5, No. 3, July, 1990, p 1426.

T. Suda and Y. Sunaga, "Calculation of Large Ion Densities Under HVDC Transmission Lines by the Finite Difference Method," IEEE Paper 95WM226-1PWRD, presented at the 1995 IEEE/PES Winter Meeting, January 29-Feb. 2, 1995, New York.

T. Suda and Y. Sunaga, "Small Ion Mobility Characteristics under the Shiobara HVDC Test Line," IEEE Transactions on Power Delivery, Vol. 5, No. 1, January, 1990, p 247.

T. Suda, "Evaluation of Ion counters Using a Facility to Produce a Steady State Ion Flow Field," IEEE Transactions on Power Delivery, Vol. 6, No. 4, October, 1991, p 1805.

V. L. Chartier, R. D. Stearns, "Examination of Grizzly Mountain Data Base to Determine Effects of Relative Air Density and Conductor Temperature on HVDC Corona Phenomena," IEEE Transactions on Power Delivery, Vol. 5, No. 3, July, 1990, p 1575.

V. L. Chartier, R. D. Stearns, A. L. Burns, "Electrical Environment of the Uprated Pacific NW/SW Intertie," IEEE Transactions on Power Delivery, Vol. 4, No. 2, April, 1989, p 1305.

W. Janischewskyj and G. Gela, "Finite Element Solution for Electric Fields of Coronating DC Transmission Lines," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-98, No. 3, May/June, 1979, p 1000.

W. Janischewskyj, P. S. Maruvada, and G. Gela, "Corona Losses and Ionized Fields of HVDC Transmission Lines," CIGRE paper 36-09, International Conference on Large High Voltage Electric Systems, Paris, September, 1982.

Hybrid AC/DC Transmission Lines

B. A. Clairmont, G. B. Johnson, L. E. Zaffanella, S. Zelingher, "The Effect of HVAC-HVDC Separation in a Hybrid Corridor," IEEE Transactions on Power Delivery, Vol. 4, No. 2, April, 1989, p 1338.

E. V. Larsen, R. A. Walling and C. J. Bridenbaugh, "Parallel AC/DC Transmission Lines Steady-State Induction Issues," IEEE Transactions on Power Delivery, Vol. 4, No. 1, January, 1989, p 677.

M. Abdel-Salam, M. El-Mohandes and H. El-Kishky, "Electric Field Around Parallel DC and Multi-Phase AC Transmission Lines," IEEE Transactions on Electrical Insulation, Vol. 25, No. 6, December, 1990, p 1145.

N. Chopra, A. M. Gole, J. Chand and R. W. Haywood, "Zero Sequence Currents in AC Lines Caused by Transients in Adjacent DC Lines," IEEE Transactions on Power Delivery, Vol. 3, No. 4, October, 1988, p 1873.

P. S. Maruvada and S. Drogi, "Field and Ion Interactions of Hybrid AC/DC Transmission Lines," IEEE Transactions on Power Delivery, Vol. 3, No. 3, July, 1988, p 1165.

R. J. Bacha, "Compatibility of HVDC and HVAC on the Same Structure or Right of Way," Paper presented at the HVDC Transmission Lines EPRI Review Meeting, Washington, D.C., April 24, 1984.

V. L. Chartier, S. H. Sarkinen, R. D. Stearns and A. L. Burns, "Investigation of Corona and Field Effects of AC/DC Hybrid Transmission Lines," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No. 1, January, 1981, p 72.

Induction on Fences and Water Pipes

C. E. Caroli, N. Santos, D. Kovarsky and L. J. Pinto, "Mitigation of Touch Voltages in Fences and Water Pipes, Caused by Itaipu HVDC Ground Return Current," IEEE Transactions on Power Delivery, Vol. 2, No. 1, January, 1987, p 281.

N. Mohan, F. S. Mahjouri and J. R. Gemayel, "Electrical Induction on Fences Due to Faults on Adjacent HVDC Transmission Lines," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No. 8, August, 1982, p 2851.

Interference With Communications: Telephone Lines and Power Line Carrier

F. S. Prabhakara and I. Vancers, "Telephone Noise Induction Analysis for Square Butte HVDC Transmission Line," IEEE conference paper A 78 585-2 presented at the IEEE/PES Summer Meeting, Los Angeles, CA, July 16-21, 1978.

N. A. Patterson, "Carrier Frequency Interference from HVDC Systems," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-104, No. 11, November, 1985, p 3255.

Ozone Production

J. G. Droppo, "Field Determination of HVDC Ozone Production Rates," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No. 2, February, 1981, p 655.

Reports

Influence of Load Current on the HVDC Corona Environment, Bonneville Power Administration, U. S. Department of Energy Report, February, 1981.

Joint HVDC Agricultural Study, Bonneville Power Administration, U. S. Department of Energy Report, September, 1988.

Study of Electric Field and Ion Effects of HVDC Transmission Lines, U. S. Department of Energy Report DOE/RA/50153-T2, August, 1985.

Books

Transmission Line Reference Book HVDC to +/- 600 kV, Electric Power Research Institute, Palo Alto, CA, 1977.

Transmission Line Reference Book - 345 kV and Above, Second Edition, Electric Power Research Institute, Palo Alto, CA, 1982.

Standards

IEEE Guide for the Measurement of DC Electric Field Strength and Ion Related Quantities, IEEE Standard 1227-1990 (Reaffirmed 1995), Institute of Electrical and Electronics Engineers, Piscataway, NJ.

IEEE Standard Definitions of Terms Relating to Corona and Field Effects of Overhead Power Lines, IEEE Standard 539-1990 (under revision 1995), Institute of Electrical and Electronics Engineers, Piscataway, NJ.

IEEE Standard for the Measurement of Audible Noise from Overhead Transmission Lines, IEEE Standard 656-1992, Institute of Electrical and Electronics Engineers, Piscataway, NJ

IEEE Standard Practices for the Measurement of Radio Noise from Overhead Power Lines and Substations, IEEE Standard 430-1986 (Reaffirmed 1991), Institute of Electrical and Electronics Engineers, Piscataway, NJ.

APPENDIX: ALTERNATING CURRENT MAGNETIC FIELDS

Electric and magnetic fields are found everywhere electricity is used. The 60-Hz magnetic field levels in homes, for example, measured near electrical appliances, range from a fraction of a milligauss to several hundreds of milligauss. The intensity of electric and magnetic fields associated with sources relate to the voltages and currents on power lines and other conductors that respectively produce them. Because residential wiring and power delivery systems carry electricity that alternates with a frequency of 60 Hz, the EMF from these facilities also oscillates at 60 Hz.

Potential Health Implications of AC Magnetic Field Exposures

Questions have been raised as to whether exposure to electric and magnetic fields in the extremely-low-frequency (ELF) range (30-300-Hz) could adversely affect human health. While there has been more than 100 years of biological research on magnetic fields, largely for basic science and potential therapeutic purposes, the speculation that magnetic fields at ELF frequencies could have adverse effects, particularly relating to cancer, has arisen mainly from epidemiologic studies reported over the past 14 years. Only magnetic field exposures are discussed because the electric field levels are attenuated and shielded by any conductive materials including buildings, fences and trees. Thus, largely precluding opportunities for significant contributions to long-term exposures from sources external to buildings. In addition, there is considerably more scientific and public concern about magnetic rather than electric field exposures because of some recent epidemiology studies.

The potential health implications of magnetic field exposures like those produced by utility distribution and transmission lines are assessed by weighing data obtained from both epidemiology studies of human populations and laboratory studies of biological responses to magnetic fields in living animals or in isolated cells and tissues.

Epidemiological Studies

Epidemiologic studies provide information directly about people and their illnesses. However, investigators have very limited control over the ascertainment of exposures, genetic make-up, and habits of people who are studied. In contrast, strict control over exposure, diet and individual characteristics is obtained only in laboratory studies, where exposures and responses can be manipulated to investigate their relationships and the mechanisms involved.

Some residential studies of magnetic field exposures to power lines report a weak association between childhood cancer and a rough, surrogate (or substitute) estimate of magnetic field exposure. For example, it has been reported that childhood leukemia is associated with magnetic field exposures estimated from power lines capable of carrying high currents (Wertheimer and Leeper, 1979; Savitz et al, 1988; London et al, 1991), or calculated annual magnetic fields from power lines (Feychting and Ahlbom, 1992). Yet, methods of estimating magnetic field exposure based upon the levels actually measured at the child's residence have not yielded any reliable associations with leukemia of children (Savitz et al, 1988; London et al, 1991; Feychting and Ahlbom, 1992). Still other studies report no associations with leukemia (Olsen et al, 1993; Verkasalo et al, 1993). Although the short-comings of these and other similar studies preclude any definitive interpretation of their significance for human health at this time, these studies have prompted interest in continuing research to determine whether chronic exposure to power frequency magnetic fields of more than 2-3 milligauss could influence cancer risks.

Other epidemiological studies have looked for associations between the occupations of people with cancer and occupations presumed to have exposures to magnetic fields. However, in the vast majority of these studies, the exposures of individuals to electric or magnetic fields have not been measured, and these workers also are likely to have been exposed to various chemicals on the job, some of which are potentially carcinogenic. Although some recent studies have attempted to characterize past exposures with measurements and evaluated chemical exposures, the findings of these studies have not been consistent.

Laboratory Research

Laboratory studies have been conducted over a wide range of magnetic field intensities at 60 Hz and similar frequencies to elicit biological responses and identify the conditions and mechanisms under which they can be produced. However, from perhaps thousands of studies in the literature, relatively few biological responses are reported to occur with exposure to 60-Hz magnetic fields at intensities less than one Gauss, and those that have been reported are not adverse. Many findings are reported not to be confirmed by other investigators. Although there is considerable interest in determining whether there is any biological basis for an association between ELF fields and cancer, the available data has not provided any substantive support for a role for magnetic fields to influence tumorigenic processes.

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52. John P. Bowles, BODEVEN, Inc., 1750 Sommet Trinite, St. Bruno, Quebec, Canada J3V
53-56. Robert H. Brewer, Department of Energy, EE-10, 1000 Independence Avenue, S.W., Washington, DC 20585
57. Vikram Budraja, Senior Vice President, Southern California Edison Company, P.O. Box 800, Rosemead, CA 91770
58. Richard Bunch, Bonneville Power Administration, P.O. Box 491, Vancouver, WA 98666
59. Mel Callen, Western Area Power Administration, P.O. Box 3700- J5500, Loveland, CO 80539-3003
60. Walter Canney, The Administrator, Lincoln Electric Company, P.O. Box 80869, Lincoln, Nebraska 68501
61. Ralph Cavanagh, Senior Attorney, National Resources Defense Council, 71 Stevenson Street, Suite 1825, San Francisco, CA 94165
62. Jim Charters, Western Area Power Administration, P.O. Box 6457- G5530, Phoenix, AZ 85005-6457

63. Mark Clements, Public Service Company of Colorado, 5909 East 38th Avenue, Denver, CO 80207
64. Carol Cunningham, Executive Vice President, Consolidated Hydro, 680 Washington Boulevard, 5th Floor, Stanford, CT 06901
65. John Dabkowski, Electro-Sciences, Inc., 7021 Foxfire Drive, Crystal Lake, IL 60012
66. Jose Delgado, Director, Electric Systems Operations, Wisconsin Electric Power, 333 West Everett Street, Milwaukee, WI 53203
67. Inez Dominguez, Public Service Company of Colorado, 5909 East 38th Avenue, Denver, CO 80207
68. Jeff Donahue, New England Power Service Company, 25 Research Drive, Westborough, MA 01582
69. Dr. Thomas E. Drabek, Professor, Department of Sociology, University of Denver, Denver, CO 80208-0209
70. Paul Dragoumis, President, PDA, Inc., P.O. Box 5, Cabin John, MD 20818-0005
71. Mike Dubach, General Electric Company, 3900 East Mexico Ave #400, Denver, CO 80210
72. Aty Edris, Electric Power Research Institute, 3412 Hillview Avenue, Palo Alto, CA 94303
73. Jack Fink, 1 South Bryn Mawr Place, Media, PA 10963
74. Doug Fisher, New England Power Service Company, 25 Research Drive, Westborough, MA 01582
75. Theresa Flaim, Vice President, Corporate Strategic Planning, Niagara Mohawk Power Corporation, 300 Erie Boulevard West, Syracuse, NY 13202
76. Mike Fredrich, Black Hills Power & Light, P.O. Box 1400, Rapid City, SD 57702
77. John Fulton, Southwestern Public Service Co., P.O. Box 1261, Amarillo, TX 79170
78. Laszlo Gyugyi, Westinghouse Science & Technology Center, 1310 Beulah Road, Pittsburgh, PA 15235

79-88. Ronald L. Hauth, New England Power Service Co., 25 Research Drive, Westborough, MA 01582

89. Dr. Stephen G. Hildebrand, Director, Environmental Sciences Division, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831-6037
90. Matthew Holden, Jr, Professor of Government & Foreign Affairs, University of Virginia, 232 Cabell Hall, Charlottesville, VA 22903
91. Richard J. Holt, NDT Engineering Inc., 787 Hartford Turnpike, Shrewsbury, MA 01545
92. Carl Huslig, West Plains Energy, 105 South Victoria, Pueblo, CO 81002
93. Bob Johnson, Western Area Power Administration, P.O. Box 3402-A3940, Golden, CO 80401
94. Bradley K. Johnson, Power Technologies Inc., P.O. Box 1058, Schenectady, NY 12301
95. Gerhard Juette, Siemens Energy & Automation, 100 Technology Drive, Alpharetta, GA 30202
96. Duncan Kincheloe, Commissioner, Missouri Public Utility Commission, P.O. Box 360, Jefferson City, MO 65102
97. Dan Klempel, Basin Electric, 1717 East Interstate Avenue, Bismarck, ND 58501
98. Henry J. Knapp, Missouri Basin Systems Group, 201 N. Minnesota Ave., Ste 102B, Sioux Falls, SD 57102-0312

99. Len Kovalsky, Westinghouse Science & Technology Center, 1310 Beulah Road, Pittsburgh, PA 15235
100. Einar Larsen, General Electric Company, Power Systems Engr. Dept., 1 River Road, Schnectady, NY 12345
101. Tom Lemak, Westinghouse Science & Technology Center, 1310 Beulah Road, Pittsburgh, PA 15235
102. Bill Long, University of Wisconsin, 432 North Lake Street, Madison, WI 53705
103. Dan Lorden, New England Power Service Company, 25 Research Drive, Westborough, MA 01582
104. Frank McElvain, Tri-State G&T, P.O. Box 33695, 12076 Grant Street, Denver, CO 80233
105. Alden Meyer, Director of Government Relations, Union of Concerned Scientist, 1616 P. Street N.W., Suite 310, Washington, DC 20036
106. Greg Miller, Public Service Company of NM, Alvarado Square, Albuquerque, NM 87158
107. Roger Naill, Vice President and Planning, AES, 10001 North 19th Street, Arlington, VA 22209
108. Bill Newman, Senior Vice President, Transmission Planning and Operations, Alabama Power, 600 North 18th Street, Birmingham, AL 35202-2625
109. Erle Nye, Chairman and Chief Executive, TU Electric, 1601 Bryan Street, Dallas, TX 75201-3411
110-113. Phil Overholt, Department of Energy, EE-11, 1000 Independence Ave., SW, Washington, DC 20585
114. Larry Papay, Sr. Vice President and General Mgr., Bechtel, P.O. Box 193965, San Francisco, CA 94119
115. Suresh Patel, Engineering Manager, Colorado Springs Utilities, P.O. Box 1103, Colorado Springs, CO 80947
116. Dusan Povh, Siemens, AG, P.O. Box 3220, D91050 Erlanger, Germany (via Air Mail)
117. Bradley D. Railing, New England Power Service Co., 25 Research Drive, Westborough, MA 01582
118. Don Ramey, Westinghouse Electric Corp., 4400 Alafaya Trail, Orlando, FL 32816
119. S. C. Rao, Colorado Springs Utilities, P.O. Box 1103, Colorado Springs, CO 80947
120. Vera Rappuhn, Plains Electric G&T, P.O. Box 6551, Albuquerque, NM 87197
121. Mark Reynolds, Bonneville Power Administration, P.O. Box 3621 - TE, Portland, OR 97208
122. Tom Rietman, Western Area Power Administration, P.O. Box 3402 - A3300, Golden, CO 80401
123. Brian Rowe, GEC Alsthom T&D, Power Electronics Systems, Lichfield Road, Stafford, ST174LN, United Kingdom (via Air Mail)
124. Steve Sanders, Western Area Power Administration, P.O. Box 35800 - B6302.BL, Billings, MT 59107-5800
125. A. Schieffer, System Planning Manager, NPPD, General Office, P.O. Box 499, Columbus, NE 68602-0499
126. Rich Sedano, Commissioner, Vermont Department of Public Service, 112 State Street, Montpelier, VT 05620-2601
127. Philip Sharp, Director, Institute of Politics, Harvard University, 79JFK Street, Cambridge, MA 02138

128. Karl Stahlkopf, Vice President, Power Delivery Group, Electric Power Research Institute, 3412 Hillview Ave., Palo Alto, CA 94303-1395
129. Marty Stenzel, ABB Power T&D Company, Inc., P.O. Box 9005, Littleton, CO 80160
130. James R. Stewart, Power Technologies Inc., P.O. Box 1058, Schenectady, NY 12301
131. Charles Stormon, CEO and Chief Scientist, Coherent Research, Inc., 1 Adler Drive, East Syracuse, NY 13057
132. Philip J. Tatro, New England Power Service Co., 25 Research Drive, Westborough, MA 01582
133. Susan Tierney, Economic Resources Group, 1 Mifflin Place, Cambridge, MA 02138
134. Duane Torgerson, Western Area Power Administration, P.O. Box 3402 - A3940, Golden, CO 80401
135. Arnold Turner, Vice President, New England Electric System, 25 Research Drive, Westborough, MA 01582
136. Randy Wachal, Manitoba HVDC Research Centre, 400-1619 Pembina Highway, Winnipeg, Maniboa R3T 2G5, CANADA
137. Dr. C. Michael Walton, Ernest H. Cockrell Centennial Chair in Engineering and Chairman, Department of Civil Engineering, University of Texas at Austin, Austin, TX 78712-1076
138. Ed Weber, Western Area Power Administration, P.O. Box 35800-B6300.BL, Billings, MT 59107-5800
139. Deborah E. Weil, Bailey Research Associates, Inc., 292 Madison Avenue, New York, NY 10017
140. Mark Wilhelm, Electric Power Research Institute, 3412 Hillview Avenue, Palo Alto, CA 94304
141. Norman Williams, Sunflower Electric Cooperative, P.O. Box 1649, Garden City, KS 67846
142. Gene Wolf, Public Service Company of NM, Alvarado Square- MS0600, Albuquerque, NM 87158
143. Dennis Woodford, Manitoba HVDC Research Centre, 400-1619 Pembina Highway, Winnipeg, Maniboa R3T2G5, CANADA

144-146. OSTI, U.S. Dept. Of Energy, P.O. Box 62, Oak Ridge, TN 37831

UNDERSTANDING ELECTRIC AND MAGNETIC FIELDS

In Association with HVDC Transmission Lines

CLEAN LINE
ENERGY PARTNERS

THIS BROCHURE IS INTENDED TO EDUCATE AND PROMOTE A FACT BASED UNDERSTANDING OF HVDC TRANSMISSION AND ASSOCIATED ELECTRIC AND MAGNETIC FIELDS.

HVDC TRANSMISSION LINES

Historically, the transfer of electricity between regions of the country has been over high-voltage alternating current (AC) transmission lines, which means that both the voltage and the current on these lines move in a wave-like pattern along the lines and continually change direction. In North America, this change in direction occurs 60 times per second (defined as 60 Hertz [Hz]). The electric power transmitted over AC transmission lines is exactly the same as the power we use every day from AC outlets, but at a much higher voltage. Over the past 40 years HVDC transmission lines have been constructed that offer significant electrical, economic, and environmental advantages over AC transmission lines for long distances. Direct Current (DC) transmission is especially suited for integrating and transporting power generated by various renewable energy sources. Unlike an AC transmission line, the voltage and current on a DC transmission line are not time varying, meaning they do not change direction as energy is transmitted.

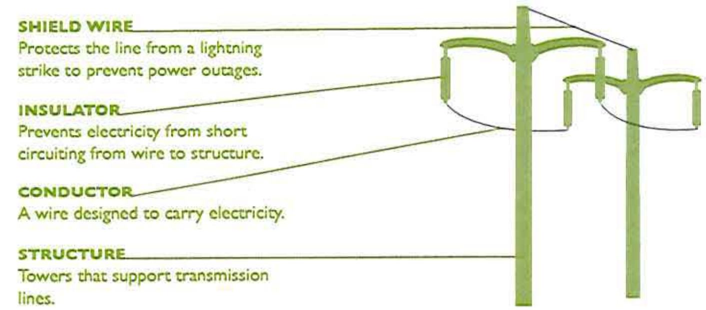
THE BENEFITS OF HVDC

MORE EFFICIENT: Over long distances, HVDC transmission can move more power with less losses versus an equivalent AC transmission line.

LOWER COST: Higher efficiency means a lower transmission cost, helping renewables compete against other power sources.

IMPROVED RELIABILITY: HVDC transmission can enhance system stability, allow the operator complete control over power flow, and facilitate the integration of wind from different resource areas.

SMALLER FOOTPRINT: HVDC transmission lines require narrower right-of-way footprints and smaller structures than equivalent AC transmission lines.



A DC transmission line has two conductor bundles called "poles." Conductors are the wires that hang from the towers and are often bundled in groups of two or three. Like a car battery, the two bundles of DC conductors have opposite polarity, one positive and one negative. The voltage of a DC transmission line, therefore, is usually referred to as ± (plus-minus) voltage. For example, a 500 kilovolt (kV) DC transmission facility would be referred to as a ± 500 kV DC transmission line.

DIRECT CURRENT (DC) The flow of electric charge is only in one direction.
ALTERNATING CURRENT (AC) The movement of electric charge that periodically reverses direction.

CURRENTLY, THERE ARE MORE THAN 20 HVDC TRANSMISSION FACILITIES IN THE UNITED STATES AND MORE THAN 35 ACROSS THE NORTH AMERICAN GRID.

DC electricity is the steady movement of electrons from an area of negative (−) charge to an area of positive (+) charge and therefore has a frequency of 0 Hz. The first commercial electric power system built by Thomas Edison in the late nineteenth century carried DC electricity, but given some early advantages, AC power eventually became the primary power system in the United States. Some of these advantages are no longer applicable (e.g., technology has advanced to allow better conversion from AC to DC), and DC transmission is the preferred solution for moving large amounts of renewable power over long distances. Currently, there are more than 20 HVDC transmission facilities in the United States and more than 35 across the North American grid (as indicated on the map to the right).

HVDC FACILITIES ACROSS NORTH AMERICA

STATIC ELECTRIC AND MAGNETIC FIELDS

DC electricity produces static electric and magnetic fields, but these fields have very different properties from AC Electric Magnetic Fields (EMF*). For example, because the EMF from AC lines are time varying, they can induce currents and voltages in nearby conductive objects. Since DC electricity does not vary over time and is static, the electric and magnetic fields from DC lines do not induce currents and voltages. Table 1 lists both natural and man-made sources of static fields. Table 2 lists the levels of static fields associated with common sources—such as cathode tube television sets, MRI machines, and stereo headphones—and illustrates that the levels of static electric and magnetic fields from DC transmission lines are lower than or in the range of natural sources of these fields.

*The abbreviation EMF is commonly used to refer to electric and magnetic fields from sources of AC electricity, not DC electricity.

TABLE 1: EXAMPLES OF NATURAL AND MAN-MAN SOURCES OF STATIC ELECTRIC AND MAGNETIC FIELDS

	NATURAL SOURCES	MAN-MADE SOURCES
ELECTRIC FIELDS	Static electricity Static cling Charges built-up in thunderstorm clouds	Electrified railways Televisions with cathode ray tubes
MAGNETIC FIELDS	The Earth	Permanent magnets Battery-powered appliances MRI machines Electrified railways

TABLE 2: STATIC ELECTRIC AND MAGNETIC FIELD LEVELS CLOSE TO COMMON SOURCES

ELECTRIC FIELDS	
Source	**Electric Field Level**
Friction from walking across carpet (at body surface)	Up to 500 kV/m
Computer screen (at 30 centimeters)	10-20 kV/m
± 500 kV DC transmission line (standing beneath conductors)	30 kV/m
MAGNETIC FIELDS	
Source	**Magnetic Field Level**
MRI machines	15,000,000 - 40,000,000 mG
Battery-operated appliances	3,000 - 10,000 mG
Electrified railways	<10,000 mG
The Earth	300 - 700 mG
± 500 kV DC transmission line (standing beneath conductors)	300 - 600 mG

*The Earth's static magnetic field level depends on location; the highest values are found at the magnetic north and south poles and the lowest values are found near the equator.
** mG: a milligauss is 1/1000th of a Gauss, which is a measure of the magnetic field. A typical refrigerator magnet will produce about 50 Gauss, or 50,000 mG.
*** kV: a Kilovolt is 1000 volts.

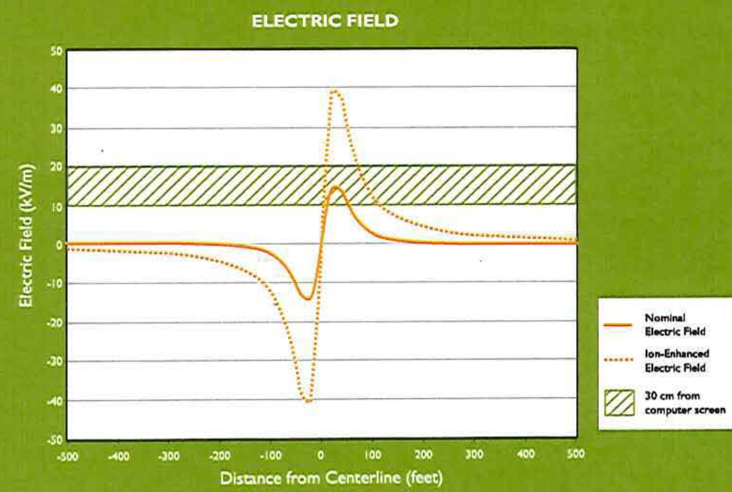
SINCE DC ELECTRICITY DOES NOT VARY OVER TIME AND IS STATIC, THE ELECTRIC AND MAGNETIC FIELDS FROM DC LINES DO NOT INDUCE CURRENTS AND VOLTAGES.

STATIC ELECTRIC FIELDS FROM DC TRANSMISSION LINES HAVE LITTLE INFLUENCE ON THE STATIC ELECTRIC FIELD LEVELS WITHIN NEARBY BUILDINGS.

STATIC ELECTRIC FIELDS

Static electric fields occur as a result of voltage and are produced by a DC transmission line's conductors and by airborne charge. Airborne charge includes air ions (air molecules that have gained or lost charges) and particles in the air that have become charged from collisions with air ions. This airborne charge is collectively referred to as space charge. Trees, bushes, and any conducting building material block static electric fields. Therefore, static electric fields from DC transmission lines have little influence on the static electric field levels within nearby buildings adjacent to the right-of-way.

A common, natural source of static electric fields is "static electricity," which results from a difference in electric potential between two points that can result in a discharge of energy. Well-known sources include the charge on the body produced by shuffling across a carpet and the strong electric fields produced by the "static cling" of clothing. Other common sources include the charges built-up in thunderstorm clouds and on blowing dust. The static electric field levels measured directly under DC lines fall in the range of the levels produced by these common sources.



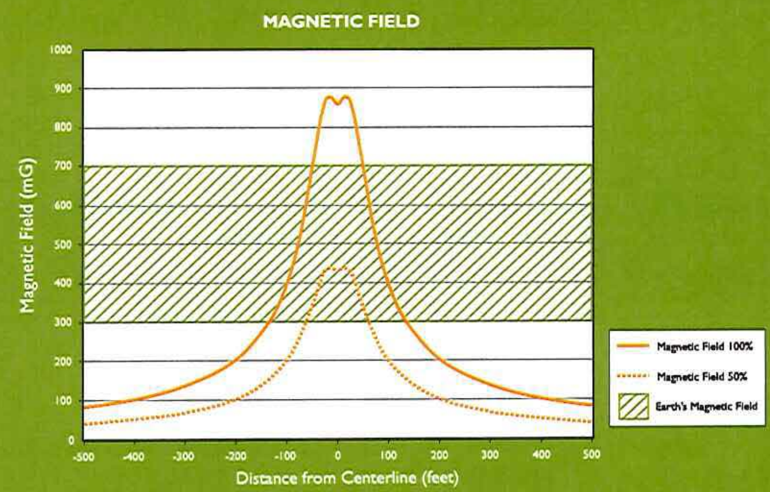
The graph above shows both the nominal electric field and ion-enhanced electric field in fair weather under a ±600 kV transmission line (similar to the lines proposed by Clean Line Energy) from the center of the line out to a lateral distance of 500 feet on each side of the transmission line. As can be seen on this plot, the electric field is highest directly under the conductors and rapidly diminishes with distance from the line. The plot illustrates that the electric field derives both from the voltage on the conductors (the nominal field in the plot) and from charges on air molecules (air ions). The contribution of air ions to the total electric field will be variable depending on weather conditions. (Source: POWER Engineers, Inc. for Clean Line Energy Partners LLC)

THE STATIC MAGNETIC FIELD LEVELS BELOW OVERHEAD DC TRANSMISSION LINES ARE SIMILAR TO OR LESS THAN THE STATIC MAGNETIC FIELD OF THE EARTH.

STATIC MAGNETIC FIELDS

Static magnetic fields are created by the flow of DC electricity. The major source of static magnetic fields in our environment is the steady flow of currents deep in the Earth's outer liquid core and from metallic elements in the Earth's crust. This constant and ever-present field is what causes compass needles to orient in a north-south direction. Depending on the orientation of a DC transmission line, the magnetic field from the transmission line can either increase or decrease the Earth's DC magnetic field.

Other common sources of static magnetic fields include permanent magnets (which are found in appliances, toys, and medical devices), battery-powered appliances, magnetic resonance imaging (MRI) machines, some electrified railway systems, and certain industrial processes. MRI machines produce static magnetic fields in the range of 15-40 million milligauss (mG), while the Earth's static magnetic field ranges from 300-700 mG (Table 3). The static magnetic field levels below overhead DC transmission lines are similar to or less than the static magnetic field of the Earth. Unlike static electric fields, static magnetic fields are not blocked by most objects.



This graph shows the magnetic field under a ±600 kV transmission line (similar to the lines proposed by Clean Line Energy) from the center line out to a lateral distance of 500 feet on each side of the transmission line with full load current (100% load producing highest magnetic field) flowing in the pole conductors. At other times the load carried will be less (50% load) and will produce a proportionally lower magnetic field. Similar to electric fields, the strength of the magnetic field diminishes very quickly moving from directly under the conductors to the edge of the right-of-way and beyond. The magnetic fields shown in this graph are on the same order of magnitude as Earth's naturally occurring magnetic field (about 300 mG to 700 mG). Outside of the right-of-way, magnetic field strengths will be lower than the fields presented everywhere and everyday due to the Earth's own magnetic fields. The static magnetic field level associated with DC transmission lines and the Earth's magnetic field are far below limits for human exposure as recommended by the International Commission on Non-Ionizing Radiation Protection (ICNIRP)[1] and the International Commission for Electromagnetic Safety (ICES)[2].

[1] The ICNIRP is a body of independent scientific experts covering Epidemiology, Biology, Dosimetry and Optical Radiation. This expertise is brought to bear on addressing the important issues of possible adverse effects on human health of exposure to non-ionising radiation.
[2] The ICES is a non-profit organization that promotes research to protect public health from electromagnetic fields and develops the scientific basis and strategies for assessment, prevention, management and communication of risk.
(Source: POWER Engineers, Inc. for Clean Line Energy Partners LLC)

REVIEWS AND STANDARDS FOR EXPOSURE TO STATIC FIELDS

Like the EMF associated with AC power, questions have been raised about the possibility that static fields affect our health. The vast majority of research has focused on the possibility that strong static field levels might have biological effects, either beneficial (i.e., therapeutic) or adverse. There is less interest in weak static field levels in the range of those produced by DC transmission lines because similar levels occur naturally. This research has been reviewed and summarized by the following organizations:

- International Agency for Research on Cancer (IARC) in 2002
- National Radiological Protection Board of Great Britain (NRPB) in 2004
- World Health Organization (WHO) in 2006
- International Commission on Electromagnetic Safety (ICES) in 2002 and 2007
- International Commission on Non-Ionizing Radiation Protection (ICNIRP) in 2009

All of these scientific panels concluded that the current body of research does not indicate that strong static magnetic fields cause long-term health effects such as cancer. Additional research is being conducted on occupational exposures in locations where work is performed in very high field levels such as certain industrial sites and near MRI units. Movement within very strong static magnetic fields of experimental MRI scanners is known, however, to cause immediate and reversible responses that are not life threatening—e.g., nausea and visual sensations. Exposure limits have been developed by the ICNIRP and ICES to avoid these effects (Table 3).

The static magnetic field levels associated with DC transmission lines and the Earth's natural magnetic field are far below these limits for human exposure.

TABLE 3: RECOMMENDED LIMITS FOR EXPOSURE TO STATIC MAGNETIC FIELDS

	ICNIRP[1]	ICES[2]
General Public	4,000,000 mG	1,180,000 mG
Workers	20,000,000 mG	3,530,000 mG

Exposure to static magnetic fields standing under a ±600 Kv HVDC transmission is less than 900mG.

[1] International Commission on Non-Ionizing Radiation Protection (ICNIRP). Guidelines On Limits of Exposure to Static Magnetic Fields. Health Physics 96:504-514, 2009.
[2] <0.153Hz, International Committee on Electromagnetic Safety (ICES). IEEE Standard for Safety Levels with Respect to Human Exposure to Electromagnetic Fields 0 to 3 kHz C95. 6-2002. Piscataway, NJ: IEEE, 2002. Reaffirmed 2007.

THE CURRENT BODY OF RESEARCH DOES NOT INDICATE THAT STRONG STATIC MAGNETIC FIELDS CAUSE LONG-TERM HEALTH EFFECTS.

Like static magnetic fields, static electric fields do not induce voltages and currents in the body. Unlike magnetic fields, static electric fields do not enter the body. High levels of static fields can sometimes be perceived by the movement of body hair and cause effects similar to those associated with static electricity. Clean Line Energy follows recommendations of the Health Protection Agency of Great Britain (formerly the NRPB) to minimize sensations associated with static electric fields.

CORONA PHENOMENA

Corona refers to the partial electrical breakdown by the electric field of the air surrounding points on the conductor surface of transmission lines. This breakdown results in the release of small amounts of energy that may be detected near the line as audible noise and 'static' on radio and television receivers. Clean Line projects will be designed to meet U.S. Environmental Protection Agency (audible noise)[1] and IEEE (radio/TV noise)[2] guidelines.

Corona also creates air ions, which are molecules that have temporarily gained or lost electrons. Air ions occur as a result of geologic, atmospheric, weather-related, and combustion phenomena, e.g., flames. Most air ions from DC transmission lines are carried to the ground or the opposite polarity conductor, but some remain in the air for seconds before contacting an opposite charge or transferring charge to small aerosol particles. Air ions and charges on aerosols collectively are called "space charge," and their presence adds to the DC static electric field created by the conductors. Space charge has been studied for over one hundred years and no health agency has confirmed any health risk of this natural phenomenon or proposed health-based exposure limits.

1 U.S. Environmental Protection Agency (USEPA). Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety. Office of Noise Abatement and Control, March 1974.
2 IEEE Committee Report. Radio Noise Design Guide for High Voltage Transmission Lines. IEEE Transactions on Power Apparatus and Systems, PAS-90: 833-842, 1971.

ELECTRONIC DEVICES

The static fields of DC transmission lines are too weak to affect the operation of implanted medical devices such as cardiac pacemakers. Like AC transmission lines, the corona on DC lines can produce AM radio and TV audio signal interference within about 100 feet of the lines. The possibility of interference to cell phones, GPS receivers, etc., is unlikely.

FARM AND RANCHING OPERATIONS

Studies performed for a federal agency on the effects of a DC transmission line reported that the line did not affect crops, vegetation, or nearby wildlife, nor were the fields perceived by persons walking on the right-of-way.[1] Another study conducted by Oregon State University reported no differences between cattle and crops raised under a ±500 kV DC transmission line and those raised in a control location away from the line[2]. A study of over 500 herds of dairy cattle in Minnesota reported that multiple indicators of herd health including milk production per cow, reproductive efficiency, and milk fat content did not differ in the periods before and after a DC line was energized, nor did they differ if a herd was close to or far from the DC line[3].

1 Griffith DB. Selected Biological Parameters Associated with a ±400 kV DC Transmission Line in Oregon. A Report by the Western Interstate Commission for Higher Education for the Bonneville Power Administration, Portland, OR, 1977; Lee JM, Jr. and Griffith DB. Transmission Line Audible Noise and Wildlife. In JL Fletcher and RG Busnel (eds). Effects of Noise on Wildlife. New York: Academic Press, 1978
2 Raleigh RJ. Joint HVDC Agricultural Study: Final Report. Oregon State University. Report for Boneville Power Administration, 1988.
3 Martin FB, Bender A, Steurnagel G, Robinson RA, et al. Epidemiologic study of Holstein dairy cow performance and reproduction near a high-voltage direct-current powerline. J Toxicol Environ Health 19:303-324, 1986.

SUMMARY

HVDC technology has been developed to transmit large amounts of electricity across long distances. Because of its advantages over AC technology, HVDC has been employed in many transmission projects worldwide.

The static fields associated with DC transmission lines are in the range of those associated with common, natural sources. The static magnetic field levels associated with DC transmission lines are approximately 1,200 to 8,000 times lower than the guidelines proposed by ICES and ICNIRP, respectively. Static electric fields may be perceived outside the right-of-way by the movement of hair on the surface of the body at lower levels, but the electric field from DC transmission lines is usually too weak to be perceived. The scientific literature establishes that DC transmission lines do not pose health or safety issues for humans or animals.

ABOUT CLEAN LINE ENERGY

AN EFFECTIVE SOLUTION TO THE NATION'S TRANSMISSION CHALLENGE REQUIRES THE APPROPRIATE TECHNOLOGY AND THE RIGHT PROJECTS. CLEAN LINE IS DEVELOPING A PORTFOLIO OF PROJECTS THAT HAVE A SIMILAR, COMPELLING RATIONALE – THE DELIVERY OF THOUSANDS OF MEGAWATTS OF RENEWABLE POWER FROM THE WINDIEST AREAS OF THE UNITED STATES TO AREAS THAT HAVE A DEMAND FOR CLEAN ENERGY BUT LACK ACCESS TO CLEAN ENERGY RESOURCES.

THESE PROJECTS WILL HELP MAKE POSSIBLE:

- CREATION OF THOUSANDS OF CONSTRUCTION AND PERMANENT JOBS
- BILLIONS OF DOLLARS OF INVESTMENTS IN NEW RENEWABLE ENERGY PROJECTS
- RURAL ECONOMIC DEVELOPMENT
- THE REDUCTION OF CARBON POLLUTION BY MILLIONS OF TONS
- INCENTIVES TO MANUFACTURE WIND TURBINES AND COMPONENTS
- PROPERTY TAX REVENUE FOR LOCAL COMMUNITIES
- LANDOWNER ROYALTIES

CLEAN LINE'S MANAGEMENT TEAM INCLUDES HIGHLY REGARDED PROFESSIONALS IN THE ELECTRIC ENERGY INDUSTRY. COLLECTIVELY, THE CLEAN LINE TEAM HAS ORGANIZED THE FINANCING OF BILLIONS OF DOLLARS OF PROJECTS AND MANAGED THE DEVELOPMENT AND CONSTRUCTION OF THOUSANDS OF MEGAWATTS OF GENERATION AND TRANSMISSION LINES.

CLEAN LINE
ENERGY PARTNERS

1001 MCKINNEY, SUITE 700 HOUSTON, TX 77002 TEL 832.319.6310 FAX 832.319.6311

CLEANLINEENERGY.COM